

1 **Venusian Habitable Climate Scenarios: Modeling Venus**
2 **through time and applications to slowly rotating**
3 **Venus-Like Exoplanets**

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9 **Key Points:**

- 10 • Venus could have had habitable conditions for nearly 3 billion years.
11 • Surface liquid water is required for any habitable scenario.
12 • Solar insolation through time is not a crucial factor if a carbonate-silicate cycle
13 is in action.

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Abstract

One popular view of Venus’ climate history describes a world that has spent much of its life with surface liquid water, plate tectonics, and a stable temperate climate. Part of the basis for this optimistic scenario is the high deuterium to hydrogen ratio from the Pioneer Venus mission that was interpreted to imply Venus had a shallow ocean’s worth of water throughout much of its history. Another view is that Venus had a long lived (~ 100 million year) primordial magma ocean with a CO_2 and steam atmosphere. Venus’ long lived steam atmosphere would sufficient time to dissociate most of the water vapor, allow significant hydrogen escape and oxidize the magma ocean. A third scenario is that Venus had surface water and habitable conditions early in its history for a short period of time ($< 1\text{Gyr}$), but that a moist/runaway greenhouse took effect because of a gradually warming sun, leaving the planet desiccated ever since. Using a general circulation model we demonstrate the viability of the first scenario using the few observational constraints available. We further speculate that Large Igneous Provinces and the global resurfacing 100s of millions of years ago played key roles in ending the clement period in its history and presenting the Venus we see today. The results have implications for what astronomers term “the habitable zone,” and if Venus-like exoplanets exist with clement conditions akin to modern Earth we propose to place them in what we term the “optimistic Venus zone.”

Plain Language Summary

We have little data on our neighbor Venus to help us understand its climate history. Yet Earth and Venus are sister worlds: they initially formed close to one another, and have nearly the same mass and radius. Despite the differences in their current atmospheres and surface temperatures, they likely have similar bulk compositions, making comparison between them extremely valuable for illuminating their distinct climate histories. We analyze our present data on Venus alongside knowledge about Earth’s climate history to make a number of exciting claims. Evaluating several snapshots in time over the past 4+ billion years, we show that Venus could have sustained liquid water and moderate temperatures for most of this period. Cloud feedbacks from a slowly rotating world with surface liquid water reservoirs were the keys to keeping the planet clement. Contrast this with its current surface temperature of 450 degrees and an atmosphere dominated by Carbon Dioxide and Nitrogen. Our results demonstrate that it was not the gradual warming of the sun over the eons that contributed to Venus present hot-house state. Rather we speculate that large igneous provinces and the global resurfacing 100s of millions of years ago played key roles in ending the clement period in its history.

1 Introduction

The case for prolonged habitability of Venus has been made by a number of authors in recent years (e.g., Grinspoon & Bullock, 2007; Way et al., 2016). If so, then if habitability was widespread and persisted over geological timescales (e.g. 10^9 years), it is possible that organisms were capable of filling a large variety of environmental niches as occurred on Earth via evolutionary processes. This has led to speculation about possible remaining life-friendly niches (e.g., Morowitz & Sagan, 1967; Grinspoon, 1997; Cockell, 1999; Schulze-Makuch & Irwin, 2002; Schulze-Makuch et al., 2004; Dartnell et al., 2015; Limaye et al., 2018). These possibilities alone provide sufficient motivation to understand whether early Venus was habitable or not. However, Venus is also interesting from the perspective of the large number of rocky exoplanets discovered to date inside the traditional inner edge of the habitable zone but far enough from their host stars to maintain an atmosphere (Kane et al., 2019). If some of these planets in close proximity to their host stars have long periods of habitability it may overturn traditional notions of the habitable zone (e.g., Kopparapu et al., 2013) and influence target selection

64 for characterization of the atmospheres of these planets. Hence, what appears to be a
 65 modern Venus-like world close to its parent star might host surface liquid water. We re-
 66 fer to such habitable worlds as residing in an “Optimistic Venus Zone,” a subset of the
 67 planets in the “Venus Zone” described in Kane et al. (2014).

68 There are three primary requirements for the early habitability of Venus. The first
 69 is that temperatures were low enough that liquid water was capable of condensing on
 70 the surface of Venus. The second is that Venus had a sufficient inventory of water to cre-
 71 ate the conditions believed necessary for the rise of life on terrestrial worlds (e.g., Brack
 72 et al., 2010). Third, volatile cycling and a geologically active surface must exist to reg-
 73 ulate the climate as possibly supported by the work of Noack et al. (2012). For surficial
 74 water reservoirs most research has focused on the poorly constrained measurement of
 75 the D/H ratio of $\sim 150 \pm 30$ (times Earth’s value) by the Pioneer Venus Mission¹ (Donahue
 76 et al., 1982, 1997). A number of other ground based measurements have been made (De Bergh
 77 et al., 1991; Marcq, 2006; Bjoraker et al., 1992; Fedorova et al., 2008) that have gener-
 78 ally revealed values of D/H greater than 100. For a recent review of D/H measurements
 79 of Venus see Section 6.3 of Marcq et al. (2017). We review the work of authors who have
 80 considered Venus’ climate evolution below.

81 The first simple gray radiative transfer calculations of Venus’ climate history sug-
 82 gested an early runaway greenhouse effect (e.g., Ingersoll, 1969; Rasool & de Bergh, 1970).
 83 Any water would have remained in vapor form throughout Venus’ early history until its
 84 loss to space via photodissociation processes (Goody & Walker, 1972; Walker, 1975). CO₂
 85 would continue to be outgassed and would accumulate (offset by atmospheric loss over
 86 the last 4.5Gyr) to the values we see today.

87 Pollack (1971) used a similar model but with non-gray radiative transfer. This was
 88 probably the first work to show that Venus could have hosted liquid water on its sur-
 89 face in its early history, but they also demonstrated that a runaway greenhouse was pos-
 90 sible as well. The difference between the two outcomes was *mostly* due to the spec-
 91 ified cloud cover and water vapor content of the atmosphere. With 50% cloud fraction
 92 the result was usually a runaway greenhouse. For an N₂ dominated atmosphere with a
 93 modern Earth water vapor profile, 100% cloud cover, and a 30% less luminous sun (akin
 94 to ~ 4.5 Ga) he achieved surface temperatures ~ 300 K. These purely radiative models did
 95 not include convection, which would limit the water vapor mixing ratio by precipitation
 96 and limit the lapse rate of temperature to the moist adiabatic value (Rampino & Caldeira,
 97 1994) and lessen the strength of the greenhouse effect to some degree. Likewise, they did
 98 not include an atmospheric general circulation that would determine the cloud fraction
 99 self-consistently. Donahue and Pollack (1983) replicated some aspects of the Pollack (1971)
 100 work and again showed that clement conditions were possible in Venus’ early history.

101 Kasting et al. (1984) used a 1-D radiative-convective model to demonstrate that
 102 a planet with an insolation $S_0X=1.45$ times that of modern Earth ($1973 \text{ W m}^{-2} \sim 3.8$ Gya
 103 at Venus’ orbit) would have temperatures $\sim 100^\circ \text{ C}$ for a 2 bar N₂ H₂O atmosphere. This
 104 atmosphere contained a wet stratosphere, and thus photodissociation of H₂O and sub-
 105 sequent escape of hydrogen (e.g., Goody & Walker, 1972) could explain the long-term
 106 loss of Venus’ primordial ocean and its present dry conditions. In a subsequent study
 107 Kasting (1988) claimed that clouds would cool the atmosphere enough to keep it in a
 108 moist greenhouse state, rather than the runaway state. At the same time the Kasting
 109 (1988) surface temperature for his “Early Venus” (Figure 7) cloud-free model was ~ 500 K
 110 and hovered just at the margin of the moist vs. runaway greenhouse states. Thus it was
 111 clear early on that maintaining liquid water on ancient Venus required high fractional
 112 cloud cover, but whether physical mechanisms exist to produce these cloudy conditions
 113 was not addressed. These early Venus habitability scenarios would have taken place within

¹ https://nssdc.gsfc.nasa.gov/planetary/pioneer_venus.html

114 the first billion years of the planet’s evolution limiting the possibility for complex life to
 115 evolve. Venus would have subsequently entered a moist/runaway greenhouse and left us
 116 with the state it is in today. For the curious reader Bullock and Grinspoon (1999) pro-
 117 vide a nice review of the literature on the possibility of an early habitable Venus. Note
 118 that in a previous work (Way et al., 2016) it was shown that if habitable conditions were
 119 possible in early Venus’ history that it likely remained so and that increasing solar in-
 120 solation through time is not a deciding factor. In the present work we find the same, and
 121 hence believe that limited (in time) early habitability models are not supported by our
 122 simulations.

123 Grinspoon and Bullock, in a number of abstracts (e.g., Grinspoon & Bullock, 2003;
 124 Grinspoon, 2008), described a Venus climate evolution scenario with long-lived surface
 125 habitability consistent with that described later in this paper. This work was never pub-
 126 lished, though, so the details of their calculations and the justifications for their conjec-
 127 tures are not documented.

128 The first three-dimensional (3-D) General Circulation Model (GCM) exploration
 129 of issues relevant to ancient Venus was that of Abe et al. (2011). Their study focused
 130 on land planets (analogous to the planet Arrakis of *Dune*) with no permanent surface
 131 water reservoirs, only limited fixed amounts of ground water. In some scenarios they found
 132 that “in principle Venus could have been a habitable land planet as recently as 1 billion
 133 years ago.” Their conclusions resulted from the limited water vapor in the atmosphere
 134 caused by the modest subsurface reservoir, its limited greenhouse effect, and the albedo
 135 of the planet. Thereafter Leconte et al. (2013) used a 3-D GCM to look at climate sce-
 136 narios for Gl581 c and HD 85512 b. HD 85512 b orbits a K-dwarf with a synchronous
 137 rotation period of ~ 58 days and receives approximately 1.86 times the insolation of present
 138 day Earth. This is slightly less than present day Venus’ insolation (1.9), but its host star
 139 is a K-dwarf rather than a G-dwarf and hence the peak of its Planck blackbody spec-
 140 trum is at longer wavelengths. They state, “if not for its thick atmosphere, Venus’ cli-
 141 mate would be very close to the one of HD 85512 b.” They modeled a dry planet akin
 142 to that of Abe et al. (2011) using an N_2 dominated atmosphere with 376ppm CO_2 , and
 143 no water vapor. The model produced large temperate regions for a number of different
 144 atmospheric pressures (See Leconte et al. (2013) Figures 1, 2) for their land planet setup,
 145 but they also found similar behavior in their ‘collapse’ scenario with different atmospheric
 146 water vapor profile amounts.

147 A rationale for high albedo cloud cover on ancient Venus was first presented by Yang
 148 et al. (2014). Yang et al. (2014) was a large parameter study looking at the inner edge
 149 of the habitable zone around solar type stars using a modern GCM² with comprehen-
 150 sive atmospheric physics but a thermodynamic ocean (Way et al., 2017).³ In essence they
 151 stepped the sidereal rotation rate of an Earth-like world from 1 to 256 sidereal days. At
 152 the same time they increased the insolation from that of modern Earth to as much as
 153 2.6 times the modern Earth for their most slowly rotating world of 256 sidereal days pe-
 154 riod. One of their key conclusions was that the slowest rotators would have had a day-
 155 night general circulation that would generate an optically thick contiguous cloud bank
 156 in the substellar region. This cloud deck would greatly increase the planetary albedo,
 157 keeping the surface temperature moderate even for quite high values of insolation. These
 158 results were later confirmed with a completely different 3-D GCM with a fully-coupled
 159 dynamic ocean (Way et al., 2018). Yang et al. (2014) also included a simulation with mod-

² The National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM).

³ A thermodynamic ocean, also known as a slab or mixed-layer ocean, is typically of limited depth (<100 meters) with a prescribed horizontal ocean heat transport, or no horizontal heat transport at all. The latter implies that the temperature of each ocean grid cell is determined solely by the atmosphere and incident sunlight directly above it. The shallow depth reduces the time lag between solar forcing and ocean response. See Way et al. (2017) Section 2.2.2 for details.

ern Venus orbital parameters, spin rate, insolation while using modern Earth topography and land/ocean mask, but again with a thermodynamic ocean. These studies provide a possible rationale for the cloud cover needed to produce temperate surface conditions as first postulated by Pollack (1971). Finally Way et al. (2016, hereafter Paper I) took things one step further by exploring different topographies, insulations and rotation rates to put tighter constraints on possible habitable conditions for ancient Venus.

In this paper, we extend those parameter studies to consider a wider variety of planets and attempt to justify our modeling assumptions in light of possible scenarios for Venus’ evolution. Sections 2–5 review existing observational constraints and hypotheses about the composition, thickness, and evolution of Venus’ atmosphere and water history; its surface and interior; and its rotation and obliquity. In Section 6 we draw upon this information to inform a series of 3-D global climate model simulations to illustrate possible scenarios for an early habitable Venus that transitioned to its current inhospitable state relatively late in its history. We discuss the implications of our results for the design of future missions to Venus and for the potential habitability of exoplanets inside the inner edge of the traditional “habitable zone” in Section 7. Finally, recently published complimentary work by Weller and Kiefer (2019) supports many of our conclusions.

2 Atmospheric Composition and Pressure

Assuming that Venus and Earth formed from the same parts of the protoplanetary disk and thus with similar compositions (e.g., Raymond et al., 2004), we are guided by the history of Earth whose early atmosphere was likely CO₂-rich and possibly cool, but not frozen due to the faint young sun for the late Hadean and early Archean (4.2-4.0 Ga) (e.g., Owen et al., 1979; Kasting, 1993; Zahnle & Sleep, 2002; J. W. Valley et al., 2002; Zahnle, 2006; Zahnle et al., 2010; Kunze et al., 2014; Catling & Kasting, 2017; Krissansen-Totton et al., 2018; Mello & Friaa, 2019; S. J. Mojzsis et al., 2019)⁴. The picture of a “Cool Early Earth” promoted in the early 2000s by J. W. Valley et al. (2002); J. Valley (2005) and with more recent zircon data (Valley et al., 2014) may also be applicable to Venus’ early evolutionary history if Venus survived its magma ocean (MO) phase with some liquid surface water. Chassefière et al. (2012) was probably the first to make the comparison of Hadean Earth with Venus, calling his hypothesis a “cool early Venus.”

The prospects for a cool early Earth and Venus hypothesis have improved in recent years, while the likelihood for their end in a cataclysmic “late instability” known as the Late Heavy Bombardment (LHB) may have started to fall out of favor. The LHB is important because its intensity was imagined so intense that the surface temperatures of Earth would return to those before the cool early Earth period, perhaps evaporating the oceans and/or raising surface temperatures to values exceeding 100°C. However, in recent years a number of studies have started to question the timing and strength of the LHB (e.g. Boehnke & Harrison, 2016; Zellner, 2017; Morbidelli et al., 2018; Quarles & Kaib, 2019; S. J. Mojzsis et al., 2019)⁵. An “early instability” has started to gain favor in what is termed an “accretion tail” scenario. This accretion tail scenario has recently been promoted in the works of Morbidelli et al. (2018, Figure 1) and S. J. Mojzsis et al. (2019, Figure 1). More recent work by de Sousa Ribeiro et al. (2020) demonstrates that the instability⁶ has a median timescale of 36.78-61.5 *Myr* and is within 136 *Myr* in 75% of their cases. de Sousa Ribeiro et al. (2020) say the timing of an early instability fits in nicely with the survival of the Patroclus–Menoetius Jupiter Trojan as a primordial binary from the Kuiper Belt (Nesvorný et al., 2018) and is a good match to other so-

⁴ For Catling and Kasting (2017) see section 11.4

⁵ For a brief overview of the latest work on the LHB see Mann (2018) and Voosen (2020).

⁶ In these works a late or early heavy bombardment is triggered by a period of orbital ‘instability’ experienced by the giant planets as described in de Sousa Ribeiro et al. (2020).

lar system properties (e.g. Clement et al., 2019), but they explicitly discuss the many limitations of their model. In the spirit of an early instability and accretion tail scenario, Figure 4 of S. J. Mojzsis et al. (2019) suggests that Venus accreted less than 0.01 wt% between 4.3 and 4.1Ga, about the same as Earth. As S. J. Mojzsis et al. (2019) notes, “Results show that an abating impact flux from late accretion is inadequate to sterilize the surface zone.” These works demonstrate the possibility that the cool early Earth continued through the originally proposed time period of the LHB from ~ 3.8 –4.1Ga. Hence we will begin our most ancient Venus simulations with CO₂ dominated atmospheres at ~ 4.2 Ga (during the J. W. Valley et al. (2002) cool early Earth period) that evolves over time to N₂ dominated atmospheres. If the LHB were a real event we would want to begin our simulations at 3.8Ga, rather than 4.2Ga, as others have speculated previously (e.g., Rampino & Caldeira, 1994; Lammer et al., 2018). There are still many unanswered questions regarding the early post-MO history of the atmospheres of Venus, Earth and Mars. Even though we have far more information to discern Earth’s early post-MO atmosphere it remains a complicated story yet to be fully resolved (e.g., Hirschmann, 2012; Nikolaou et al., 2019) and may depend on atmospheric pressure more than previously assumed (e.g., Gaillard & Scaillet, 2014; Bower, Dan J. et al., 2019).

The carbonate-silicate cycle (e.g., Walker et al., 1981; Stewart et al., 2019) is the key to keeping most of Earth’s CO₂ locked up in rocks for much of its history rather than in the atmosphere as on present day Venus. The carbonate-silicate cycle on Earth functions via subductive-type plate tectonics, the presence of a hydrosphere and continental crust. For Earth there are several lines of evidence to suggest these may go back to the Hadean (e.g., S. Mojzsis et al., 2001; Hopkins et al., 2008; Harrison, 2009; Korenaga, 2013; Harrison et al., 2017; O’Neill et al., 2017; Rozel et al., 2017; Kusky et al., 2018; Korenaga, 2018; Maruyama et al., 2018, and references therein). Dehant et al. (2019) reviews the literature for a later beginning of plate tectonics on Earth (Section 3.2). The requirements for how plate tectonics begins are still not fully understood and hence remains an active area of research (e.g., Lenardic et al., 2019). If Venus had a similar early atmospheric and interior evolution to that of Earth then early volatile cycling via some form of plate tectonics is a viable hypothesis.⁷ Hence in our scenario a carbonate silicate cycle is hypothesized for Venus after the magma ocean phase and well before its resurfacing period to keep CO₂ largely sequestered in crustal carbonates as on modern Earth.

We are motivated to choose 1 bar atmospheres for our epochs of interest based on geological atmospheric pressure proxies for Earth that imply an atmospheric density of ~ 0.25 –1.1bar for most of the past 4 billion years (Nishizawa et al., 2007; Goldblatt et al., 2009; D. Som S. Catling et al., 2012; S. Som et al., 2016; Marty et al., 2013; Avicé et al., 2018). However, some models of Nitrogen cycling imply that the atmospheric pressure could have been higher in the Archean (Johnson & Goldblatt, 2015; Mallik et al., 2018). Differences in N₂ of factors of a few have relatively small net impacts on climate, primarily due to small decreases/increases in the pressure broadening of CO₂ lines and partly offsetting decreases/increases in Rayleigh scattering. Given the likely similar geochemistry and volatile histories of Venus and Earth (e.g., Ringwood & Anderson, 1977; Lécuyer et al., 2000; Treiman, 2009; Chassefière et al., 2012; Rubie et al., 2015), a similar evolution in their early composition and pressure histories is plausible. Although whether they did indeed start out with similar volatile inventories is still an open research question (e.g. Horner et al., 2009).

Additional work demonstrates that the present day CO₂ and N₂ inventories of Earth and Venus may be similar (Donahue & Pollack, 1983; Goldblatt et al., 2009) if Venus

⁷ In fact recent work demonstrates convection regimes like that of plate tectonics in Venus’ recent history (Gillmann & Tackley, 2014; Davaille et al., 2017). Dehant et al. (2019) reviews plate tectonic mechanisms that may not require as much water as previously believed, which may be relevant if Venus retained some water but less than Earth.

254 is more degassed than Earth as Donahue and Pollack (1983) speculated. Early work by
 255 Rasool and de Bergh (1970) and Kasting (1988) estimated nearly as much CO₂ was locked
 256 up in carbonate rocks on Earth as exist in the atmosphere of Venus. Since there is no
 257 carbonate-silicate cycle active on Venus today most of the CO₂ that would otherwise be
 258 locked up in the interior is in the atmosphere, having degassed over the past several hun-
 259 dred million years (at least). As well, nearly 4 times as much N₂ is found in Venus' present
 260 day atmosphere as in Earth's when scaled by planetary mass. Earth's internal N₂ bud-
 261 get is estimated at $\sim 7 \pm 4$ times that of the atmospheric mass (Johnson & Goldblatt,
 262 2015).

263 However, Argon (Ar) modeling studies (Kaula, 1999; ORourke & Korenaga, 2015)
 264 imply that Venus is less degassed than Earth, although see Donahue and Pollack (1983)
 265 and Halliday (2013) for alternative explanations for the current ⁴⁰Ar abundance differ-
 266 ence between Earth & Venus. Watson et al. (2007) claims that ⁴⁰Ar is not a reliable in-
 267 dicator of degassing, although “the interpretation of their data is controversial” accord-
 268 ing to ORourke and Korenaga (2015). Halliday (2013) also mentions that Venus' radio-
 269 genic ⁴⁰Ar implies Venus is less degassed than Earth, but he notes that Venus' atmospheric
 270 non-radiogenic ³⁶Ar has concentrations roughly two orders of magnitude greater than
 271 Earth's and that “this is hard to explain unless it (Venus) is heavily degassed with a larger
 272 inventory of primordial volatiles.” In further support of a degassed Venus Halliday (2013)
 273 notes that the similar Earth and Venus budgets of C and N support a degassed Venus
 274 while helping to explain the high ²⁰Ne and ³⁶Ar budgets of Venus. One of the largest
 275 stumbling blocks in deciding whether the ⁴⁰Ar modeling inference is correct is a proper
 276 measurement of K/U on Venus, which is presently highly unconstrained. For this rea-
 277 son modeling studies generally use Earth values. Namiki and Solomon (1998) use He to
 278 confirm the ⁴⁰Ar estimates, but they require a Venus in-situ mission to make the appro-
 279 priate Th and U abundance measurements to characterize the geochemistry necessary
 280 for He production. One also needs to consider He escape, an under-explored area of re-
 281 search given that it depends not only on the ability of He to remain charged or neutral,
 282 but also whether Venus had a past magnetic field and how present day measurements
 283 can distinguish in situ He in the upper atmosphere from solar wind deposition.

284 Another limiting factor in comparing Earth and Venus is the lack of good constraints
 285 on the bulk water content of Earth. Some papers refer only to surface water amounts
 286 of 0.023 wt% of the Earth's total mass, but there are compelling arguments for possi-
 287 bly deep reservoirs within the lower mantle or core (e.g., Raymond et al., 2006; Schmandt
 288 et al., 2014; Genda, 2016; Ikoma et al., 2018). For Venus, interior water amount estimates
 289 are mostly speculation and are restricted to planetary formation studies (e.g., Ikoma et
 290 al., 2018).

291 **3 Venus' Early Evolution & Evidence for Water**

292 Venus & Earth likely received similar initial water inventories during their forma-
 293 tion histories, as has been shown in a number of works (e.g., Raymond et al., 2006). It
 294 is also tied to their composition in general, as discussed above in Section 2.

295 The Pioneer Venus mass spectrometer measured a very high D/H ratio of 150 ± 30
 296 times that of terrestrial water (Donahue et al., 1997) in a trapped droplet of sulfuric acid.
 297 It is the only such published in-situ measurement. Other non in-situ measurements have
 298 been made as noted in Section 1, and work continues apace (e.g. Tsang et al., 2017). The
 299 original Venus D/H discovery paper by Donahue et al. (1982) was titled “Venus was Wet:
 300 A measurement of the Ratio of Deuterium to Hydrogen.” This was a tantalizing prospect,
 301 but limited by our knowledge of atmospheric escape processes (Donahue & Pollack, 1983;
 302 Donahue & Russell, 1997; Donahue, 1999) and the D/H of delivered materials over the
 303 aeons.

304 It is possible that the D/H ratio is not an indicator of large amounts of water in
 305 Venus’ ancient history. Grinspoon (1993) pointed out that a short residence time for wa-
 306 ter in the present atmosphere of Venus works against the primordial ocean hypothesis.
 307 Grinspoon (1993) also noted that updated theoretical calculations at that time that im-
 308 plied higher deuterium escape efficiency put constraints on the D/H source water of 10-
 309 15. That would rule out source material such as meteorites, comets and dust particles
 310 with high D/H ratios (e.g., Irvine et al., 2000; Charnley & Rodgers, 2009). As well, mea-
 311 surements of D/H and Xenon isotopes in Comet 67P (Altwegg et al., 2015; Marty et al.,
 312 2017) imply that Earth’s ocean has a much lower contribution from cometary objects
 313 than previously thought. This would also likely rule out a large cometary contribution
 314 to the high D/H ratio measured on Venus.

315 A number of authors have tried to model changes in the D/H fractionation over
 316 time (Kasting & Pollack, 1983; Gurwell & Yung, 1993; Gurwell, 1995; Hartle et al., 1996)
 317 to put some constraints on when the water was lost. Given the lack of data from Venus
 318 it is equally difficult to constrain or move these models forward.

319 The possibility that the high D/H ratio implies long-lived surface water is also lim-
 320 ited by in-situ measurements. There is some circumstantial evidence of past surface wa-
 321 ter from surface emissivity observations from the Galileo NIMS instrument (Hashimoto
 322 et al., 2008) and the Venus Express VIRTIS instrument (Mueller et al., 2008). These ob-
 323 servations may imply that the highland “tessera” regions are mostly composed of felsic
 324 rocks, and if they are indeed granitic they would have required surface water to form (Campbell
 325 & Taylor, 1983). M. S. Gilmore et al. (2015); M. Gilmore et al. (2017) find that at least
 326 one tessera region observed with VIRTIS (Alpha Regio) appears to be more felsic than
 327 surrounding plains. This also suggests that these older stratigraphic units (Ivanov & Basilevsky,
 328 1993; M. S. Gilmore et al., 1997) are granitic crustal remnants, but recent work by Wroblewski
 329 et al. (2019) shows that parts of the Ovda Regio highland tessera are not in fact of granitic
 330 origin. However, it is not yet possible to generalize the work of Wroblewski et al. (2019)
 331 to the entirety of tessera.

332 Nikolayeva (1990) and Shellnutt (2019) analyzed surface rock measurements from
 333 Venera 8. As Shellnutt (2019) explains “it is possible that the Venera 8 probe encoun-
 334 tered a fragment of crust that resembles a terrestrial greenstone belt.” Zolotov et al. (1997)
 335 and Johnson and Fegley (2000) have also demonstrated that signatures of water in hy-
 336 drous minerals may persist on the surface of Venus for long periods even after the sur-
 337 face morphology has changed. This motivates an in-situ mission to Venus to search for
 338 such materials, if they exist. Watson et al. (2007) tried to demonstrate that the ^{40}Ar in
 339 Earth’s atmosphere is related to the hydration of the oceanic lithosphere consisting of
 340 relatively Ar-rich olivine and orthopyroxene. If the results from Watson et al. (2007) are
 341 correct, (and there is skepticism (Ballentine, 2007)), this would lead one to believe that
 342 the ^{40}Ar in Venus’ atmosphere today implies that water oceans could have persisted for
 343 some time.

344 An outstanding unsolved and understudied problem is what happened in the epoch
 345 of Venus’ MO as it cooled, as this may greatly affect the long-term water inventory of
 346 the planet. The timescale of the MO crystallization could be of order a few million years
 347 (*Myr*) as for Earth (e.g., Katyal et al., 2019; Nikolaou et al., 2019) or greater than 100
 348 *Myr* (Hamano et al., 2013; Lebrun et al., 2013). The longevity of the MO and associ-
 349 ated hot steam and CO_2 atmosphere is vital to understanding the volatile history of Venus
 350 (e.g. Salvador et al., 2017). If the MO and steam atmosphere persist too long then much
 351 of the primordial water inventory of Venus could have been lost in its very early history
 352 from a stronger solar wind (Chassefière, 1997; Lichtenegger et al., 2016). An attractive
 353 feature of the extended MO hypothesis is that it naturally solves the problem of the lack
 354 of oxygen in the present day Venusian atmosphere. This would be accomplished by se-
 355 questrating the O_2 left behind by H_2O dissociation in the magmatic crust and upper man-
 356 tle (e.g. Lebrun et al., 2013; Gillmann et al., 2009; Lichtenegger et al., 2016; Lammer

et al., 2018). We discuss how large quantities of O_2 can be lost after a significant period of habitability in bullet 6 of Section 8, in lieu of early MO losses. It is possible that the high D/H ratio we see today (Donahue et al., 1982, 1997) is a relic of the early MO period. If the MO cooled quickly, then there was an opportunity to build up a surface ocean and atmosphere as is believed to have happened in Earth’s early history. The question is whether Venus’ surface conditions as a result of its closer proximity to the Sun would prevent the condensation of water on its surface or not. The answer is more complicated than it may seem since water can condense under hot high pressure multi-bar atmospheres. Matsui and Abe (1986) allow for temperatures up to 600K, while later work by Liu (2004) allow temperatures approaching 720K.

Additionally the answer may reside in the planet’s rotation history, what role clouds played, and the outgassing rates of H_2O and CO_2 . As we will show in Section 5 it is possible for Venus to reach a tidally locked state in less than a few hundred *Myr* using constant phase lag dissipation theory, suggesting that the planet’s rotation rate could have been slow early on. As shown in previous work (Way et al., 2016, 2018) as long as a planet is in the slowly rotating regime (length of day greater than ~ 16 Earth sidereal days) its climate dynamics work to allow liquid water to persist on the surface for insulations up to ~ 2.6 times that of present day Earth. This is due a large contiguous dayside cloud deck that significantly increases the planetary albedo as discussed in Section 4.

The timing of the MO termination is critical in more than one way. If the steam and CO_2 atmosphere cooled sufficiently for MO crystallization to occur by the time of the Late Veneer (also referred to as “Late Accretion”) then even if Venus lost most/all of its primordial H_2O through escape processes (Gillmann et al., 2009; Hamano et al., 2013; Lichtenegger et al., 2016) there may have been a second chance to obtain a surface ocean, albeit a shallow one. Recent work by Greenwood et al. (2018) implies that Earth may have received as much as 30% of its H_2O inventory in post-accretion impact delivery, consistent with research that shows that the entire H_2O budget cannot come from the late veneer (Morbidelli & Wood, 2015). Halliday (2013) concludes that if veneers were common they should be proportional to planetary mass, and hence Venus would have received a percentage of late veneer H_2O similar to that of Earth. If Venus was left dry after a long-lived magma ocean phase (Hamano et al., 2013), then this amount of H_2O veneer also fits within the error bounds of Venus’ measured D/H ratio (Donahue et al., 1982, 1997). It should be noted that the work of Greenwood et al. (2018) can also fit within the Ruthenium studies of Fischer-Gödde and Kleine (2017). For a contrary point of view see Gillmann et al. (2019), who claim that most of the late veneer impactors would have been Enstatite/ordinary chondrites which are water-poor, as opposed to water-rich carbonaceous chondrites that would have been a mere 0-2% of the total chondrite delivery. These contrary points of view come about because different geochemical measurements give different answers as pointed out in a number of recent works (e.g. Albarède, 2009; Fischer-Gödde & Kleine, 2017; Dauphas, 2017; McCubbin & Barnes, 2019; Zahnle et al., 2019). There are two other important caveats to consider regarding the late veneer. First the water content depends upon the composition of the accreting bodies. For example, if the late veneer was made up of a few large bodies then the variations could have been greater than if it was due to a large collection of smaller bodies. Second, the definition of the late veneer is important since it is typically associated with the accretion of bodies after the last giant impact. Jacobson et al. (2017) has suggested that the last giant impact on Venus could have been much earlier than on Earth and this obviously affects the composition of objects making up the late veneer.

At the same time, work by Gillmann et al. (2009), Morbidelli et al. (2000), and Raymond et al. (2006) shows that Venus’ initial water inventory at formation could be as much as two terrestrial ocean’s worth while large planetary embryos could deliver much more within 200 *Myr* of formation. If true, and if the magma ocean lifetime on Venus was shorter rather than longer, then our estimates of the water content on Venus from Pioneer Venus

410 D/H ratios (Donahue et al., 1982, 1997) should be more toward the higher end, $\sim 16\%$
 411 of a present day Earth’s ocean (Donahue et al., 1997). However, it is not clear whether
 412 Venus’ primordial water content can readily be constrained by the D/H ratio (Grinspoon,
 413 1987; Grinspoon, 1993) due to a lack of knowledge of sources and sinks over the lifetime
 414 of the planet.

415 Another hypothesis (e.g., Rampino & Caldeira, 1994) states that because of its prox-
 416 imity to the Sun, Venus could never condense water on its surface and hence its surface
 417 temperature has always been 300K or higher (see Figure 1 in Rampino & Caldeira, 1994)
 418 and that most of this water was lost by photodissociation (Goody & Walker, 1972). At
 419 the same time the lack of water prevents silicate rock weathering (on Earth this removes
 420 CO_2 from the atmosphere), hence the CO_2 builds up in the atmosphere driving temper-
 421 atures ever higher due to the greenhouse effect as seen today.

422 4 Surface History, Impactors and Climate Evolution

423 Understanding the surface history of Venus is crucial to constraining any theory
 424 of its long-term climate evolution. Smrekar et al. (2018) reviews the literature on Venus’
 425 internal structure and dynamics. In this section we mostly focus on implications for the
 426 surface features we see today and how those might be consistent with a hypothesis for
 427 the long-term habitability of Venus and a transition to a more recent ($\sim 1\text{Gyr}$) hothouse
 428 state.

429 Up to 80% of the Venus surface has volcanic plains and tectonic structures emplaced
 430 over a relatively short geological interval as determined from crater counts (Ivanov & Head,
 431 2013, 2015). The cratering record seen in the plains regions imply surface ages ranging,
 432 for example, from $\sim 180\text{Ma}$ (Bottke et al., 2016), to $\sim 300\text{Ma}$ (Strom et al., 1994) to $\sim 750\text{Ma}$
 433 (McKinnon et al., 1997). The relative youth of most of Venus’ surface may be the re-
 434 sult of a large scale lithospheric overturn known as the Global Resurfacing Event (GRE),
 435 or it may be due to the latest GRE in a long sequence of episodic resurfacing events (e.g.,
 436 Turcotte, 1993; Strom et al., 1994). For example, Kaula (1999) constructed a simple model
 437 with outgassing events staggered at time periods of 4.1, 3.8, 3.5, 3.1, 2.6, 2.1, 1.5 and
 438 0.7 Ga constrained by ^{40}Ar measurements. The other hypothesis for the young surface
 439 of Venus is from continuous volcanic resurfacing (e.g. Basilevsky et al., 1997; Bjornes
 440 et al., 2012; King, 2018).

441 The highland tesserae may be one of the keys to understanding this history. They
 442 are of particular interest because they may contain information about past crustal dif-
 443 ferentiation and other processes prior to the loss of any surface water. Some crater age
 444 estimates from the Magellan Mission imply that the tesserae are $\sim 40\%$ older than the
 445 plains (Ivanov & Basilevsky, 1993; M. S. Gilmore et al., 1997). However, Strom et al.
 446 (1994) did not agree with this conclusion. Additional work by V. Hansen and López (2010)
 447 points to the possibility that the Ribbon Tessera Terrain are older than the surface units
 448 identified with the GRE. Later analysis by Ivanov and Head (2013) implied that tessera
 449 are the oldest stratigraphic unit and that they were created near the beginning of Venus’
 450 surface observable history during the “tectonically dominated regime.”

451 However, *how* the large basaltic plains were emplaced remains controversial. A num-
 452 ber of authors (e.g., Herrick, 1994; Strom et al., 1994; Basilevsky & Head, 1996) postu-
 453 lated a nearly global ($\sim 80\%$) geologically instantaneous ($10\text{-}100\text{Myr}$) thick ($>1\text{km}$) de-
 454 position of basaltic material from volcanic type outflows (GIBVO) that would have buried
 455 older craters we cannot observe today (akin to the GRE mentioned above). The outflow
 456 depth requirements are determined by the size of the largest impact craters that would
 457 have to be completely covered. However, as Ivanov and Head (2013) point out it is pos-
 458 sible that the cratering record previous to GIBVO could have also been erased in some
 459 manner. The GIBVO model was later augmented and became known as the global stratig-

460 raphy hypothesis (e.g., Basilevsky & Head, 1996; Basilevsky et al., 1997; Basilevsky &
 461 Head, 1998; Head & Basilevsky, 1998). Yet another hypothesis to explain the Venus sur-
 462 face record was initially put forward by Phillips et al. (1992) and is termed the Equilib-
 463 rium Resurfacing Model (ERM). In this model the number of craters observed on Venus
 464 today is the result of an equilibrium between constant crater formation (via impacts) and
 465 the removal of such craters via on-going tectonic or volcanic methods. Monte Carlo cal-
 466 culations by Bullock et al. (1993) and Strom et al. (1994) demonstrated why the ERM
 467 was not feasible. Strom et al. (1994) decided that the GIBVO was a better fit to their
 468 data, while Bullock et al. (1993) preferred a longer timeline of $550 Myr$. More recent Monte
 469 Carlo calculations by Bjonnes et al. (2012) show that the ERM is able to fit the obser-
 470 vations.

471 V. Hansen and Young (2007) strove to demonstrate why none of these hypothe-
 472 ses fit all available observational constraints. V. Hansen and Young (2007) then proposed
 473 what they termed the Spatially Isolated Time-Transgressive Equilibrium Resurfacing (SPIT-
 474 TER) hypothesis to explain more of the observational constraints. It is not clear that
 475 the Venus geological community has settled on any of these hypotheses. Perhaps one of
 476 the largest problems with the global lava hypothesis is the timescale, volume and depth
 477 of the basaltic flows required, none of which have been observed on any present or pre-
 478 viously active volcanic body in the solar system (including in Earth’s past). The largest
 479 known outflow to date in Earth’s history is the mid-Cretaceous Superplume (Larson, 1991),
 480 which is small by comparison to those envisioned to describe Venus’ resurfacing. At the
 481 same time the superplume hypothesis for Venus is compelling as large amounts of CO_2
 482 could have been released at the same time as the plume event (Caldeira & Rampino, 1991).
 483 Large overturn events have been proposed as an explanation for Venus’ present surface
 484 state, but in such a scenario it is possible to sequester large amounts of CO_2 in fresh flood
 485 basalt outflows due to enhanced planetary weatherability (e.g., Goddard et al., 2003; Cox
 486 et al., 2016). Large Igneous Provinces (LIPs), on the other hand, can release copious amounts
 487 of CO_2 sequestered in some sedimentary materials (e.g., Ganino & Arndt, 2009) while
 488 avoiding the sequestration issues of a large overturn event. LIPs have been proposed as
 489 an explanation for Venus’ present day state as we will discuss below.

490 Previous simulations by Way et al. (2016) showed that Venus could have had tem-
 491 perate conditions for nearly 2 billion years providing it had a shallow ocean of 310m in
 492 depth, slow rotation rate, and modern orbital elements. Venus might even have experi-
 493 enced more stable conditions than Earth in its early history since studies by Correia
 494 and Laskar (2001) and J. W. Barnes et al. (2016) have shown that low obliquity states
 495 (like that of modern Venus) may be stable over billions of years and we know that the
 496 much shorter Milankovich cycles have had a strong influence on Earth’s climate through
 497 time. Deitrick et al. (2018) reviews the influence of such cycles on the climate of Earth
 498 and possible influences on exoplanets. In addition, Weller et al. (2018) has also shown
 499 from geological models that early Venus could have avoided glaciations more easily than
 500 early Earth, which experienced several partial or total snowball periods in its history.
 501 If long-term stable surface conditions are a requirement for life, Venus might have been
 502 more stable and allowed primitive life to fill more ecological niches more quickly than
 503 on Earth. This gives rise to the possibility that life may still exist in Venus’ upper at-
 504 mosphere (Limaye et al., 2018).

505 Ernst et al. (2017) speculate that “On Venus, voluminous LIP volcanism produced
 506 high levels of CO_2 that led to run-away greenhouse effect, and high levels of SO_2 that
 507 caused acid rain,” but with little supporting evidence. Bullock and Grinspoon (2001)
 508 present a similar hypothesis that involves outgassing of SO_2 and H_2O that eventually
 509 drive the planet, over 100s of Myr , into a runaway greenhouse state, but do not men-
 510 tion CO_2 . If Venus had LIP volcanism then CO_2 as well as SO_2 can be outgassed if trapped
 511 in sediments in the crust as is seen on Earth (e.g., J. W. Head III & Coffin, 1997; V. L. Hansen,
 512 2007; Ernst et al., 2017; Ernst & Youbi, 2017). Hence if Venus had an earlier epoch of

513 liquid water habitability then it is logical to assume that CO₂ would have been trapped
 514 in the crust of the planet in the same way it is trapped on Earth today and LIP volcan-
 515 ism would have been the means to release that CO₂ into the atmosphere.

516 However, as noted in Macdonald and Wordsworth (2017) when the surface tem-
 517 perature is warmer ($T > 300\text{K}$, see their Figure 2) more water vapor is injected into the
 518 stratosphere, which stabilizes the lapse rate. Such warm climates (as seen in the Venus
 519 models herein) would prevent the largest plumes from injecting SO₂ into the stratosphere,
 520 allowing CO₂ warming without offsetting cooling by H₂SO₄ aerosols.

521 Another well known mechanism to get Venus from a cool clement state to its present
 522 day hot and dry state was proposed by a number of authors (e.g. Ingersoll, 1969; Kast-
 523 ing & Pollack, 1983; Kasting et al., 1984; Kasting, 1988; Taylor & Grinspoon, 2009) who
 524 speculated that water loss via upper atmospheric dissociation and then hydrogen escape
 525 would have eventually made the planet dry. Then, as stated in Taylor and Grinspoon
 526 (2009) “With the loss of water, the removal mechanism for CO₂ would be eliminated,
 527 and carbonate rocks on the surface would presumably eventually be subducted and lost
 528 to thermal decomposition, with the CO₂ being irreversibly returned to the atmosphere
 529 through outgassing.” This model fits in with more recent research by R. D. Wordsworth
 530 (2016a) who states that the oxygen left over would eventually find its way to oxidize the
 531 mantle and change its redox state, allowing for enhanced nitrogen outgassing which is
 532 compatible with the nearly 3 bars of N₂ we see in Venus’ atmosphere today (also see re-
 533 view by Lammer et al. (2018)). However, an alternative hypothesis is proposed by Gillmann
 534 et al. (2009), who suggest that the oxidation of the mantle occurred in the first 100 *Myr*
 535 of Venus’ history. They assume the surface was never cool enough to allow liquid wa-
 536 ter to condense. The water would again be photodissociated and the hydrogen would
 537 have been lost to space (Lichtenegger et al., 2016). The leftover oxygen would have dis-
 538 solved in the magma ocean.

539 Genda and Abe (2005) have proposed that the lack of water on Venus and in Venus’
 540 protoplanetary impactors in its early history (in contrast to that of Earth and its wa-
 541 ter rich impactors) would explain differences in most of the noble gas abundances be-
 542 tween Venus and Earth because oceanic protoplanets would enhance atmospheric loss,
 543 implying that Venus’ original noble gas abundant proto-atmosphere survived to present
 544 day on Venus, unlike that of Earth. A lack of water being detrimental to subductive plate
 545 tectonics (see Section 8). Sakuraba et al. (2019) have also attempted to get the presently
 546 observed nitrogen and noble gas abundances via impact degassing and atmospheric ero-
 547 sion (also see work by, Pham et al., 2011), but unlike Genda and Abe (2005) they be-
 548 lieve late accretion may have further influenced the atmosphere of Venus.

549 More recent work by Gillmann et al. (2016) show that large impactors (400-800km
 550 in diameter) can cause atmospheric erosion and escape and deposit energy in the crust
 551 and mantle. They believe the latter can cause a thermal anomaly in the crust and man-
 552 tle triggering large scale volcanic events at the impact region and the antipode. This in
 553 turn may deplete the upper mantle of volatiles and lead to water loss in the early atmo-
 554 sphere, or conversely provide a volatile heavy atmosphere with extreme temperatures
 555 for billions of years. In a sense this is similar to a theory by Davies (2008) who propose
 556 a mega-collision (akin to that of the Earth’s moon-forming impact) to dry out the in-
 557 terior of the planet. But thus far no large Venus impactor simulations have been utilized
 558 to examine such a scenario, as has been done for Earth’s moon-forming collision (e.g.,
 559 Canup, 2004).

560 To summarize, a number of mechanisms exist by which early Venus could have con-
 561 densed liquid water on its surface. The key ingredient is that it must have been cool enough
 562 for long enough in its early history. As shown by Yang et al. (2014); Way et al. (2016,
 563 2018), the rotation rate of a planet greatly affects its climate dynamics. Specifically, for
 564 very slow rotation a large contiguous water cloud forms at the substellar point, increas-

ing the Bond albedo markedly and keeping surface temperatures moderate for insolation values up to nearly three times that of modern Earth's 1361 W m^{-2} . In Paper I Way et al. (2016) we demonstrated that early Venus could have had consistently habitable conditions throughout its early history if it began with sufficiently slow rotation. In the next section we review what is understood about the possible evolution of Venus' spin-orbit state.

In our scenario, early Venus' has the earliest consistent liquid water habitability in the solar system followed by Earth and then Mars. This is a broader statement of the Faint Young Sun Paradox (FYSP), the challenge of explaining how early Earth, not to mention Mars, could have been warm and wet early in their histories when the Sun was 25-30% dimmer than today (e.g., Feulner, 2012). There is still debate in the ancient Earth GCM community about the actual composition and thus temperature of early Earth's atmosphere given observational proxies for CO_2 that span orders of magnitude, though models suggest that the range encompasses several viable scenarios (e.g., Charnay et al., 2013; Wolf & Toon, 2013; Kunze et al., 2014; Le Hir et al., 2014; Charnay et al., 2017; Krissansen-Totton et al., 2018). These GCM studies and most proxies (e.g., Spencer, 2019) are from the Archean rather than the late Hadean, but there is some evidence that habitable surface conditions existed well back into the Hadean (e.g., Harrison, 2009; Arndt & Nisbet, 2012).

It is interesting to note that recent atmospheric pressure proxies from the late Archean imply an atmospheric pressure less than half that of today (D. Som S. Catling et al., 2012; S. Som et al., 2016). Atmospheres thinner than modern Earth's are less likely to avoid snowball conditions, yet the literature above notes that there is geological evidence that Earth was not in a snowball state during much of the late Archean that the pressure proxies correspond to. Regardless, for this reason we feel it is necessary to explore the possibilities of lower atmospheric surface pressures in Venus' climatic history as described for Simulations 26-30 in Section 6.

The FYSP for Mars remains difficult to resolve (e.g., R. D. Wordsworth, 2016b) partly due to the fact that 3-D GCMs have traditionally struggled to consistently sustain large-area liquid water conditions over millions of years (e.g., Goldblatt et al., 2009; Kasting, 2010; Kienert et al., 2012; Feulner, 2012; Haqq-Misra et al., 2008) without snowball type conditions. Long-standing solutions involving large amounts of atmospheric CO_2 are inconsistent with unobserved carbonate deposits expected from such CO_2 dominated atmospheres (Shaw, 2018) and are insufficient in isolation to produce above-freezing conditions. One possible solution to the lack of surface carbonates was proposed by Kasting (2012). Other solutions to Mars' FYSP exist that involve H_2 with CO_2 as the background gas (e.g. R. Wordsworth et al., 2017; Ramirez, Kopparapu, Zuger, et al., 2014; Ramirez & Craddock, 2018; Haberle et al., 2019), although presently there appears to be little consensus in the community.

5 Rotation and Obliquity evolution

To the best of our abilities we would like to constrain the obliquity and rotational history of Venus to better constrain these important inputs for climate models. This is limited by the absence of any direct information about Venus' initial rotation and obliquity and the fact that impacts likely play a significant role in the early rotational history of the terrestrial planets (e.g., Lissauer & Kary, 1991; Dones & Tremaine, 1993). On Earth a variety of means exist to obtain some constraints using dynamical modeling combined with geological data when available (e.g., Hays et al., 1976; Park & Herbert, 1987; Imbrie et al., 1992; Matthews et al., 1997; Petit et al., 1999; Pälike & Shackleton, 2000; Pälike et al., 2004; Olsen et al., 2019) and there has been modest success doing the same for Mars (e.g., Cutts & Lewis, 1982; Laskar et al., 2002, 2004; Byrne, 2009; Dickson et al., 2015; Bierson et al., 2016). For Earth, an additional constraint is provided

616 by the Moon, which has predictably affected the evolution of Earth’s rotation and damped
 617 obliquity excursions over its history (Zahnle & Walker, 1987; Lissauer & Chambers, 2011).
 618 However, until and unless geological observables become available to constrain dynam-
 619 ical models, only plausible scenarios for the rotational and obliquity history of Venus can
 620 be defined.

621 Hoolst (2015) summarizes much of the literature on the rotational evolution of Venus
 622 throughout its history. We summarize some of the work on this subject below and add
 623 some additional estimates. First we look at the history of studies of the possible spin evo-
 624 lution of Venus.

625 In the 1960-70s several authors investigated the possibility that Venus’ rotation pe-
 626 riod was correlated with its synodic period (Goldreich & Peale, 1966; Gold & Soter, 1969,
 627 1979). Goldreich and Peale (1966) states, “the presence of the Earth may have stabilized
 628 the sidereal rotation period of Venus at the value of 243.16 days retrograde.” An equi-
 629 librium between the atmospheric and body tide of Venus was first proposed by Gold and
 630 Soter (1969) to explain Venus’ non-synchronous rotation period, based on the incorrect
 631 belief at that time that Venus always showed the same face at each inferior conjunction
 632 with Earth as proposed by Goldreich and Peale (1966).

633 The first work to analytically look at Venus’ rotation rate and the role of atmo-
 634 spheric tides was by Ingersoll and Dobrovolskis (1978) who extended the earlier work of
 635 Lord Kelvin Thomson (1882), Chapman and Lindzen (1970) and Munk and MacDon-
 636 ald (1960). They mention that “Venus probably originated with a retrograde rotation
 637 in order to have evolved to the current retrograde state.” In the 1980s this work was fur-
 638 ther extended in a series of papers (Dobrovolskis & Ingersoll, 1980; Dobrovolskis, 1980,
 639 1983). It was clear that Venus’ rotation rate was probably determined by a balance be-
 640 tween the solid body tidal dissipation and the thermal tides of its thick atmosphere with
 641 the sun. Core-mantle friction (CMF) can also play an important role in slowing the spin
 642 rate of Venus, as first explored by Goldreich and Peale (1970). Goldreich and Peale (1970)
 643 were also the first to demonstrate that core-mantle viscous coupling can drive the obliq-
 644 uity to 0° when less than 90° and to 180° if it is greater than 90° over time.

645 This remained the state of understanding of Venus’ rotational history until the early
 646 2000s when the long-term evolution of its spin state of Venus was investigated in a se-
 647 ries of papers by Correia and Laskar (2001); Correia et al. (2003); Correia and Laskar
 648 (2003), who suggested that Venus may have rotated faster in the past, and possibly pro-
 649 grade. It also became clear that at faster spin rates CMF plays an important role in slow-
 650 ing the rotation of the planet, but less so at slower spin rates.

651 Once a planet is spinning more slowly CMF may play an important role in obliq-
 652 uity variations (e.g., Correia et al., 2003). Correia and Laskar (2001) explored a num-
 653 ber of stable obliquity and spin states of Venus while more recent work by J. W. Barnes
 654 et al. (2016) has investigated how stable the obliquity of Venus might be though time.

655 The work on the thermal tides of Venus had led researchers to assume that its ef-
 656 fects would be minor (as it is for Earth) for atmospheres of modest density (e.g. 1 bar).
 657 However, more recent work by Leconte et al. (2015) has demonstrated that thermal tides
 658 arising from even 1 bar atmospheres can be significant depending on the distance to the
 659 host star and the host star’s mass. Leconte et al. (2015) show that even if modern Venus
 660 had a 1 bar atmosphere the tidal torques would still be quite significant.

661 R. Barnes (2017) used an equilibrium tide model with a constant phase lag (CPL)
 662 to find that Earth could have ended up tidally locked today (after 4.5Gyr) had it started
 663 with a rotation rate of 3 Earth Days or longer (the latter more likely if Earth had no satel-

664 lite). We have applied the same Equilibrium Tide Model (EqTide)⁸ from R. Barnes (2017)
 665 to Venus to explore how long it would take Venus to reach a tidally locked state only from
 666 solid body tides. As shown in Figure 1 using CPL theory we find that Venus could have
 667 been tidally locked within $684 Myr$ if it started with a prograde rotation period of 3 Earth
 668 days and zero obliquity. Unfortunately the EqTide model we utilize does not support
 669 retrograde spin states, but we expect the differences to be minor. We will continue to
 670 explore these issues in a future work using the simulator vplanet (R. Barnes et al., 2019)
 671 once this functionality is added. Figure 1 gives further examples for CPL and Constant
 672 Time Lag (CTL) theory results using EqTide. For input parameters we assume that the
 673 tidal dissipation factor $Q=12$ and Love number of degree 2 $k_2=0.3$. These are the same
 674 numbers used for the modern Earth in R. Barnes (2017). Recent work by Henning and
 675 Hurford (2014) demonstrates that our choice for Q may not be unreasonable for Venus.
 676 Henning and Hurford (2014) give estimates of Q for Earth-like planets (see their Fig 15,
 677 top-center-row plot) with orbital periods from 0 to 200 days. Venus' 224 d period is slightly
 678 outside the range they explore (but can be anticipated from the trend visible in their fig-
 679 ure). Our assumption of $Q=12$ is not far off the Henning and Hurford (2014) 'Warm Earth
 680 2' estimate in their Fig 15. As an aside, Q and k_2 are poorly constrained for present-day
 681 Venus. We have even fewer constraints on these values for an ancient Venus, but per-
 682 haps those values would be more Earth-like than present day Venus. For example, present
 683 day Venus' time lag may not be the same as Earth's because of higher internal temper-
 684 atures (MacDonald, 1962; Henning & Hurford, 2014). Historically Goldreich and Soter
 685 (1966) estimated that $Q < 17$ for Venus, Lago and Cazenave (1979) had values up to $Q \sim 40$
 686 while Leconte (2018) estimate $Q \sim 100$.

687 More recently Venus' tidal love number was estimated by Konopliv and Yoder (1996)
 688 using Magellan and Pioneer Venus Orbiter data to be $k_2=0.295 \pm 0.066$ implying the core
 689 is liquid (Yoder, 1997). Work by Zhang (1992); Xia and Xiao (2002) have estimated $k_2=0.18$
 690 ~ 0.26 . A smaller value ($k_2=0.17$) would imply a solidified iron core which is not con-
 691 sistent with Konopliv and Yoder (1996). Modeling work by Dumoulin et al. (2017) are
 692 consistent with the work of Konopliv and Yoder (1996) as well as our own modeling choices
 693 (discussed above) of $Q=12$ and Love number of degree 2 $k_2=0.299$ (see Table 3 in Dumoulin
 694 et al. (2017)). Regardless, if one uses higher values of Q and/or lower values of k_2 for
 695 ancient Venus it is sufficient to say that equilibrium tide theory predicts that the CPL
 696 and CTL for Venus estimates for tidal locking will be longer than those presented in Fig-
 697 ure 1. The values in Figure 1 then represent *lower limits* to tidal locking for a given start-
 698 ing rotational period. As a caveat there is a debate in the dynamics community about
 699 the appropriateness of the CPL and CTL approaches (Efroimsky & Williams, 2009; Efroim-
 700 sky & Makarov, 2013; Touma & Wisdom, 1994; Greenberg, 2009). so these tidal lock-
 701 ing timescales should be viewed with some caution in the context of the CPL and CTL
 702 models used herein. Of course we do not take into account magnetic braking to see how
 703 the Sun's natural spin-down might affect the tidal evolution of Venus, nor do we assume
 704 that Venus' orbital characteristics would have changed over the timescale of our calcu-
 705 lations, the latter being one of the criticism when applying CPL/CTL to evolving sys-
 706 tems (Efroimsky & Williams, 2009; Efroimsky & Makarov, 2013).

707 Recent work (Green et al., 2019) has investigated the influence of a hypothetical
 708 shallow ocean on Venus (water equivalent layers of ~ 330 meters deep and 830m) using
 709 present day topography and a range of initial rotation periods. The most dissipative sce-
 710 nario predicts a slow down of 72 days per million years. The latter result may be sur-
 711 prising until one recalls that tidal dissipation in Earth's oceans is larger than that of the
 712 Earth's solid body tides (e.g., Munk & MacDonald, 1960).

⁸ <https://github.com/RoryBarnes/EqTide>

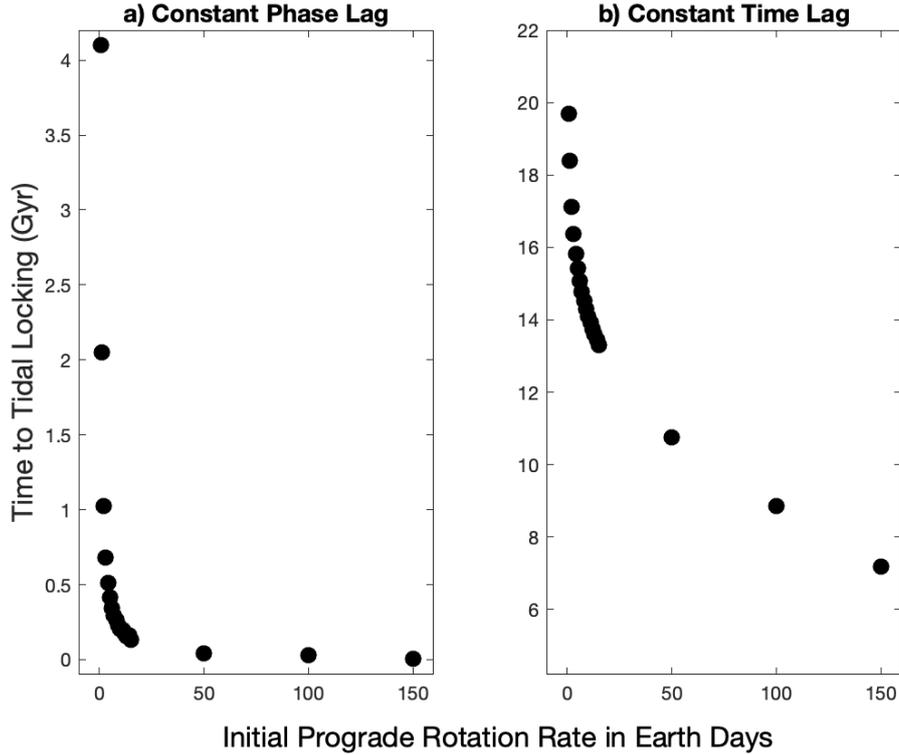


Figure 1. Venus tidal locking timescales using equilibrium tide constant phase (a) and time (b) lag theory. Note that the y-axes have different limits.

713 It is likely that Venus was initially a prograde spinning body⁹. The prograde hy-
 714 pothesis goes back at least to (Alfvn, 1964) and more recent work by Lissauer and Kary
 715 (1991); Dones and Tremaine (1993); Kary and Lissauer (1995) would also support the
 716 idea of a primordial prograde Venus, barring the effects of a late large impactor as dis-
 717 cussed in those works and that below. From that starting point we find the following per-
 718 haps the most compelling answer to Venus' present day spin state. As shown above there
 719 are models that can drive the planet toward a tidally locked state rather quickly. Core-
 720 mantle friction damps obliquity perturbations which drive the spin rate to sub-synchronous
 721 prograde rotations. Then atmospheric tides would reverse the spin to a retrograde equi-
 722 librium. These atmospheric tides continue to prevent the planet from being tidally locked
 723 and that is the state the planet has been in since that time as shown in some of the work
 724 of Correia and Laskar (2001).

725 Yet it has long been speculated that Venus' current retrograde rotation state is the
 726 result of a large impactor early in its history (McCord, 1968; Singer, 1970; French & Singer,
 727 1971; Counselman, 1973; Burns, 1973; Ward & Reid, 1973; Harris, 1978; Alemi & Steven-
 728 son, 2006; Davies, 2008). The large impactor hypothesis may also explain a possibly very
 729 dry Venus interior, a lack of oxygen in the atmosphere and reconcile the ⁴⁰Ar results that
 730 imply it is less degassed than Earth (Davies, 2008). However, as pointed out in Ward
 731 and Reid (1973) it is possible for a small impactor (less than 1% of the Moon's mass)
 732 to drive Venus retrograde if the planet has already spun down considerably due to tidal
 733 dissipation with the Sun (Figure 1).

⁹ Like the other 3 terrestrial planets in our solar system.

734 Unfortunately, there is little hope that we will ever truly know the rotation rate
 735 of Venus through time without a way to either measure its “Geological Orrery” as on
 736 Earth (Olsen et al., 2019) and tie that to dynamical models, or find evidence that an im-
 737 pactor played a role in its rotational and hence geochemical evolution as seen in inves-
 738 tigation on Earth related to late accretion and its effect on different isotope abundances
 739 (e.g., Varas-Reus et al., 2019). In fact Brassler et al. (2016) and S. J. Mojzsis et al. (2019)
 740 prefer the hypothesis that the Earth’s Late Veneer was mainly delivered by a single Pluto-
 741 or Ceres-sized impactor. Hence if a larger object was involved in the late evolution of
 742 Venus’ spin or obliquity it may be possible to detect its geochemical fingerprints in a fu-
 743 ture in-situ mission.

744 For *most* of our climate simulations we assume, rightly or wrongly as discussed above,
 745 that Venus has had the same retrograde rotation and its present day obliquity for the
 746 past 4.2×10^9 years. We have included a few faster rotation rates that approach the ‘fast
 747 rotators’ described in Yang et al. (2014); Way et al. (2018), meaning sidereal day lengths
 748 of 16 and 64 times that of present day Earth.

749 6 Methods

750 All our simulations use ROCKE-3D (Way et al., 2017) a three-dimensional (3-D)
 751 General Circulation Model (GCM) developed at the NASA Goddard Institute for Space
 752 Studies (GISS). Radiative transfer in ROCKE-3D uses k-coefficients derived from the
 753 HITRAN 2012 line list, as well as the MT-CKD 3.0 water vapor continuum and CO₂
 754 collisionally-induced absorption and sub-Lorentzian line shapes, as described in refer-
 755 ences cited in (Del Genio, Way, et al., 2019). HITRAN 2012 is accurate for temperatures
 756 below 350 K, as shown by (Kopparapu et al., 2013). As we will discuss below, a small
 757 number of our simulations exhibit a growing radiation imbalance with time, indicative
 758 of continually rising temperatures and a transition to a runaway greenhouse. If our ob-
 759 jective were to determine the threshold for a runaway, we would need to use the more
 760 comprehensive HITEMP line list for these simulations, as discussed by (Kopparapu et
 761 al., 2013). Our purpose, though, is simply to identify such cases and exclude them from
 762 further analysis.

763 Most simulations use modern Venus’ current orbital parameters, slow retrograde
 764 rotation period (-243 Earth sidereal days in length) and orbital period (224 sidereal days).
 765 In Paper I (plotted herein with ID = B) we looked at a faster rotation period (16 x mod-
 766 ern Earth’s sidereal day length) to see how the planet’s early climate might have responded,
 767 and we also look at 16 & 64 day retrograde rotation periods in Venus’ early history in
 768 this work. Our focus is on changing insolation, topography, land/sea mask, surface wa-
 769 ter availability and atmospheric constituents. We motivate our choices below.

770 All simulations discussed below are outlined in Table 1. Our focus is on the reten-
 771 tion and stability of surface liquid water on Venus over time. Therefore we simulate four
 772 types of planets with surfaces that differ in the amount of water they contain and how
 773 that water is allowed to interact with the atmosphere. ROCKE-3D allows for 3 types
 774 of surface water: Soil moisture at and beneath the surface with no standing bodies of
 775 water; “dynamic” lakes whose depth and area vary with time and that can appear or dis-
 776 appear as the competition between precipitation and evaporation dictates; and deeper
 777 oceans with permanent boundaries and an effectively infinite source of water for the at-
 778 mosphere. All planets with oceans are fully dynamic. For more details on the capabil-
 779 ities of such oceans see Way et al. (2017).

- 780 • Arid Venus: This planet has modern Venus topography, but only contains 20cm
 781 of water in the subsurface soil layers, soil consisting of 100% sand, and no surface
 782 standing water at the start of the simulation. The atmosphere is initialized with
 783 zero water vapor and an isothermal temperature profile at 300K. This initial con-

- 784 dition is similar to that of Kodama et al. (2019); Abe et al. (2011) who attempt
 785 to limit the amount of water vapor in the atmosphere (a strong greenhouse gas)
 786 and subsequently push the inner edge of the habitable zone farther inward. How-
 787 ever, Kodama et al. (2019); Abe et al. (2011) use modern Earth’s rotation rate
 788 for all their experiments.
- 789 • 10m-Venus: Uses modern Venus topography and places a 10 meter liquid water-
 790 equivalent layer in the lowest lying topographic areas. These are treated by the
 791 model as lakes, which have no circulation. The soil is a 50/50 sand/clay mix as
 792 used in Yang et al. (2014); Way et al. (2016, 2018).
 - 793 • 310m-Venus: Similar to 10m-Venus, except with a 310 meter water equivalent layer
 794 again spread in the lowest lying regions. This is the same topography used in Way
 795 et al. (2016) simulations A,B and D.
 - 796 • 158m-Aqua: This is a simple aquaplanet configuration that is commonly used in
 797 the exoplanet community. It uses a fixed 158 meter deep ocean, which corresponds
 798 to the bottom of the fifth layer of the ROCKE-3D ocean model. It is a bit shal-
 799 lower than the mean depth of the 310m-Venus ocean, and therefore comes into equi-
 800 librium a bit faster while still having a similar heat capacity, while including hori-
 801 zontal heat transport as well as wind-driven and thermohaline overturning cir-
 802 culations.
 - 803 • 310m-Earth: Similar to 310m-Venus, but using a modern Earth-like land/sea mask
 804 with a 310m deep bathtub dynamic ocean (i.e., every ocean grid cell is of a fixed
 805 depth of 310m). We call this an Earth-like land/sea mask since it is not exactly
 806 modern Earth, but has some modest changes as shown in Way et al. (2018) Fig-
 807 ure 8.

808 The five planets above are then given four types of atmospheres and four differ-
 809 ent insulations as described below:

- 810 • Simulations 1-5: These have a 10 bar 100% CO₂ atmosphere using a solar spec-
 811 trum and insolation from 4.2Ga from the work of Claire et al. (2012). CO₂ was
 812 probably the dominant gas in Earth’s early atmospheric evolution (e.g., Kasting,
 813 1993). We pick atmospheric pressures of 1 bar (see next bullet point) and 10 bar
 814 to cover the Kasting (1993) ranges (see their Fig 2). Our 10 bar results either equi-
 815 librate at a temperature beyond that at which our radiative transfer is accurate,
 816 or do not reach equilibrium and the temperatures attained at the time the exper-
 817 iments were terminated are already beyond the upper limits of our radiation ta-
 818 bles. We report the results of these experiments in Table 2 below simply as a guide
 819 for future research, but we exclude them from our analysis in Figs. 2-8. The 10
 820 bar simulations use a modern Venus rotation rate and obliquity.
- 821 • Simulations 6-10: Similar to Simulations 1-5, but these use a 1 bar 97% CO₂ and
 822 3% N₂ atmosphere at 4.2Ga.
- 823 • Simulations 11-15: As in Simulations 6-10 but with a rotation period of ~16 side-
 824 real Earth days to place the planet on the edge of the fast rotator regime as de-
 825 scribed in Yang et al. (2014); Way et al. (2018). This allows us to explore the pos-
 826 sibility that the planet was rotating more quickly in its early history than today.
 827 The choice of a retrograde rotation rate was chosen to be consistent with the present
 828 day retrograde rotation, but unpublished simulations with prograde rotation rates
 829 with these values produce very similar temperatures. Note that the work of Correia
 830 and Laskar (2001, 2003) indicate that prograde rotation rates of 16 days for Venus
 831 put its spin axis (obliquity) in a possibly chaotic regime. However, other work by
 832 J. W. Barnes et al. (2016) indicate that low obliquity retrograde rotation rates gen-
 833 erally have more stable spin axes. Even if there are spin axis variations on geo-
 834 logical timescales, it is not possible for us to model those here given that ROCKE-
 835 3D simulations are limited to < 10,000 years in length.

- 836 • Simulations 16-20: As in Simulations 6-10 but with a rotation period of ~ 64 side-
837 real Earth days. This allow us to explore the possibility that the planet was ro-
838 tating somewhat more quickly in its early history but still in the slowly rotating
839 dynamical regime. Again, prograde rotation rates were also used in unpublished
840 results and have similar global surface temperature values.
- 841 • Simulations 21-25: These simulations use an atmospheric composition and pres-
842 sure very similar to modern Earth, namely an N_2 -dominated atmosphere with 400ppmv
843 CO_2 and 1ppmv CH_4 with a 1013mb surface pressure. They also use a solar spec-
844 trum and insolation at 2.9Ga from Claire et al. (2012). The rotation rate is the
845 same as modern Venus.
- 846 • Simulations 26-30: Similar to Simulations 21-25, but with a lower atmospheric sur-
847 face pressure of 250mb. This is again in the interest of comparative climatology
848 since the Archean atmospheric pressure proxy work of D. Som S. Catling et al.
849 (2012); S. Som et al. (2016) suggests that Earth may have had a surface pressure
850 similar to 250mb at this time.
- 851 • Simulations 31-35: Similar to Simulations 21-25, but now using a solar spectrum
852 and insolation from 0.715Ga from the work of Claire et al. (2012).
- 853 • Simulations 36-40: Again, similar to Simulations 21-25, but now using a modern
854 solar spectrum and insolation.
- 855 • Simulations 41-45: Similar to Simulations 21-25, but now using a modern solar
856 spectrum, but with insolation set to 1.26 times Venus' present day insolation (2.4
857 times modern day Earth's insolation) to test the boundaries of the inner edge of
858 the habitable zone as in Way et al. (2018). Two of these simulations are also out
859 of radiation balance and trending toward a runaway greenhouse state, and thus
860 we do not analyze them further.

861 Most simulations except 158m-Aqua use a fixed ground albedo of 0.2 (thermal con-
862 ductivity = $0.26 \text{ W m}^{-1} \text{ K}^{-1}$) and 50/50 mix of sand/clay soil following the work of Yang
863 et al. (2014); Way et al. (2016, 2018). The Arid-Venus simulation uses the same albedo
864 (0.2), but utilizes a 100% sand soil, rather than the sand/clay mix in other simulations.
865 The advantage of using sand is that it more quickly loses and absorbs water. This al-
866 lows the ground hydrology to come into balance more quickly than other soil types. This
867 is because in the Arid-Venus simulations we are focused on water availability to/from
868 the atmosphere from/to the soil and hence the amount of total water vapor acting as
869 a greenhouse gas in the atmosphere.

870 7 Results and Discussion

871 Simulations 1-5, all with a 10 bar pure CO_2 atmosphere and 4.2 Ga insolation, are
872 uniformly uninhabitable regardless of the surface water reservoir and topography (see
873 Table 2 in the Supplementary Information). The driest planet (Arid Venus) does reach
874 equilibrium, but with a surface temperature of 262°C , well above the accuracy limits of
875 the radiation parameterization used by ROCKE-3D. The other four planets are also well
876 above 100°C at the point at which they were terminated and are not converging to equi-
877 librium. Given the greater water reservoirs in these simulations, they are likely to be ap-
878 proaching a runaway greenhouse state.

879 In Figure 2 we show several different possible evolutionary scenarios for Venus de-
880 rived from the other experiments in Table 1. In all such scenarios we assume that Venus
881 had surface liquid water in varying amounts at model start, as described in Section 6.
882 The colors in this figure differentiate groups of simulations with different insolation, ro-
883 tation, surface pressure, and/or atmospheric compositions, while the numbers 1-5 and
884 corresponding symbols for each color delineate the range of climates obtained for differ-
885 ent surface water reservoir and topography assumptions.

Table 1. Experiments

ID	Topography ^a	Epoch Ga	Insolation ^b S0X/W m ⁻²	P ^c bar	Spin days	N ₂ ppmv	CO ₂ ppmv	CH ₄ ppmv	Soil Type ^d
01	Arid-Venus	4.2	1.396/1913.6	10	-243	0	1000000	0	S
02	10m-Venus	"	"	"	"	"	"	"	S/C
03	310m-Venus	"	"	"	"	"	"	"	S/C
04	158m-Aqua	"	"	"	"	"	"	"	-
05	310m-Earth	"	"	"	"	"	"	"	S/C
06	Arid-Venus	4.2	1.396/1913.6	1	-16	43000	970000	0	S
07	10m-Venus	"	"	"	"	"	"	"	S/C
08	310m-Venus	"	"	"	"	"	"	"	S/C
09	158m-Aqua	"	"	"	"	"	"	"	-
10	310m-Earth	"	"	"	"	"	"	"	S/C
11	Arid-Venus	4.2	1.396/1913.6	1	-64	43000	970000	0	S
12	10m-Venus	"	"	"	"	"	"	"	S/C
13	310m-Venus	"	"	"	"	"	"	"	S/C
14	158m-Aqua	"	"	"	"	"	"	"	-
15	310m-Earth	"	"	"	"	"	"	"	S/C
16	Arid-Venus	4.2	1.396/1913.6	1	-243	43000	970000	0	S
17	10m-Venus	"	"	"	"	"	"	"	S/C
18	310m-Venus	"	"	"	"	"	"	"	S/C
19	158m-Aqua	"	"	"	"	"	"	"	-
20	310m-Earth	"	"	"	"	"	"	"	S/C
21	Arid-Venus	2.9	1.47/2001.0	1	-243	1012599	400	1	S
22	10m-Venus	"	"	"	"	"	"	"	S/C
23	310m-Venus	"	"	"	"	"	"	"	S/C
24	158m-Aqua	"	"	"	"	"	"	"	-
25	310m-Earth	"	"	"	"	"	"	"	S/C
26	Arid-Venus	2.9	1.47/2001.0	0.25	-243	1012599	400	1	S
27	10m-Venus	"	"	"	"	"	"	"	S/C
28	310m-Venus	"	"	"	"	"	"	"	S/C
29	158m-Aqua	"	"	"	"	"	"	"	-
30	310m-Earth	"	"	"	"	"	"	"	S/C
31	Arid-Venus	0.715	1.71/2358.9	1	-243	1012599	400	1	S
32	10m-Venus	"	"	"	"	"	"	"	S/C
33	310m-Venus	"	"	"	"	"	"	"	S/C
34	158m-Aqua	"	"	"	"	"	"	"	-
35	310m-Earth	"	"	"	"	"	"	"	S/C
36	Arid-Venus	0.0	1.9/2601.0	1	-243	1012599	400	1	S
37	10m-Venus	"	"	"	"	"	"	"	S/C
38	310m-Venus	"	"	"	"	"	"	"	S/C
39	158m-Aqua	"	"	"	"	"	"	"	-
40	310m-Earth	"	"	"	"	"	"	"	S/C
41	Arid-Venus	Future	2.4/3266.0	1	-243	1012599	400	1	S
42	10m-Venus	"	"	"	"	"	"	"	S/C
43	310m-Venus	"	"	"	"	"	"	"	S/C
44	158m-Aqua	"	"	"	"	"	"	"	-
45	310m-Earth	"	"	"	"	"	"	"	S/C
D ^d	310m-Venus	2.9	1.47/2001.0	1	-16	1012599	400	1	S/C

^aTopography: Arid-Venus=Only Ground Water, no surficial reservoirs, 20cm water in soil, with modern Venus topography; 10m-Venus=10m Water Equivalent Layer (WEL) spread in lowest elevations as lakes with modern Venus topography; 310m-Venus=310m deep ocean with modern Venus topography; 310m-Earth=Modern Earth-like topography with 310m deep ocean; 158m-Aqua=158m deep aquaplanet.

^bInsolation: S0X = multiple of amount that Earth receives today in insolation (S0=1361 W m⁻¹).

^c Pressure in bar. ^d S=100% Sand, S/C=50/50% Sand/Clay, - = Not Applicable, 100% ocean.

^d Simulation D from Paper 1 (Way et al., 2016). Most similar to ID 8.

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7.1 4.2Ga

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Since there are major uncertainties about what Venus' initial rotation rate was (See Section 5) we explored early post-magma ocean scenarios at 4.2Ga with three different retrograde initial rotation periods in the left hand part of Figures 2,3,4: -16 days (gray; experiments 6-10), -64 days (magenta; experiments 11-15) and -243 days (red; experiments 16-20). Each assumes a 1 bar CO₂-dominated atmosphere. As one would expect

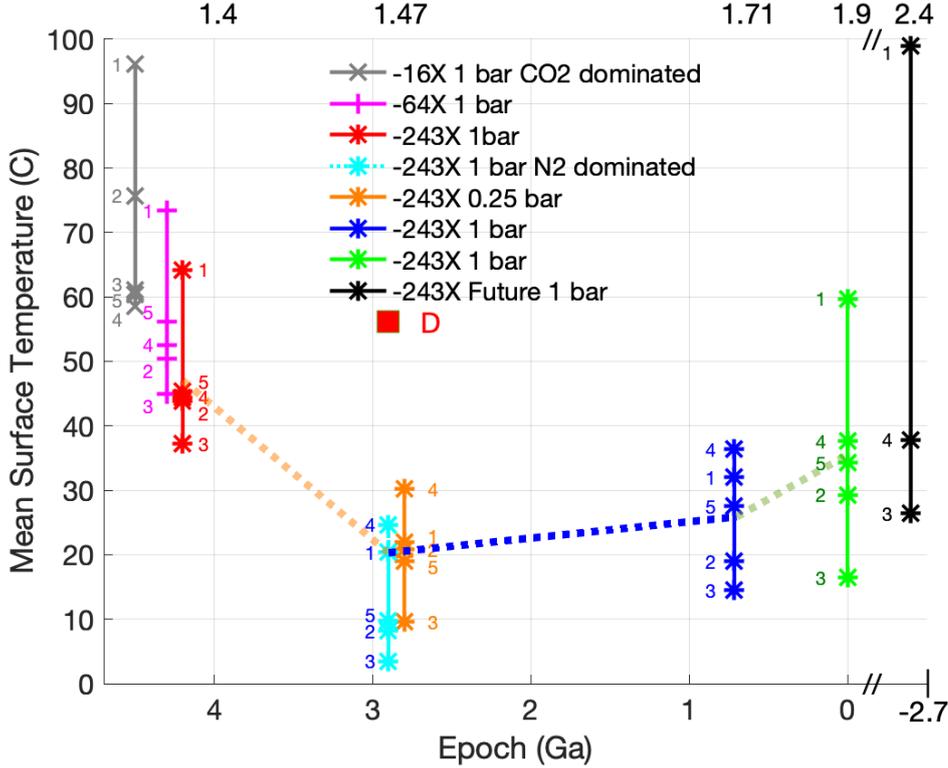


Figure 2. Atmospheric evolutionary scenarios for Venus. Top x-axis is insolation relative to modern Earth ($1.4 = 1.4 \times 1361 \text{ W m}^{-2}$). Note that the gray, magenta and red data in the left-most section of this plot are all for 4.2 Ga simulations. They are separated purely for visual effect and do not reflect differences in epoch or insolation. The same is true for the cyan, and orange data, all of which correspond to 2.9 Ga. The numbers oriented vertically along each set of simulations correspond to the different water reservoir/topography types: 1=Arid-Venus, 2=10m-Venus, 3=310m-Venus 4=158m-Aqua, 5=310m-Earth. See Table 2.

892 from the studies of Yang et al. (2014); Way et al. (2018) the faster spin rate simulations
 893 generally have higher temperatures because of the cloud processes discussed in those pa-
 894 pers, but almost all of them reach equilibrium at a habitable global mean surface tem-
 895 perature. However, the clouds also differ to some degree because of water availability.
 896 Contrary to the work of Abe et al. (2011); Kodama et al. (2019) the Arid-Venus cases
 897 all have higher surface temperatures than their counterparts. This is because those pre-
 898 vious works used modern Earth’s rotation rate, whereas the cloud processes on these slower
 899 rotating worlds better regulate the climate, more so the more water that is available for
 900 cloud formation. This analysis is backed up by Figure 3 where we plot the shortwave cloud
 901 radiative forcing (SWCRF). The Arid-Venus simulations have the smallest (in magni-
 902 tude) values, because a drier planet has less reflective clouds with less condensed water.
 903 In Figure 4 we show the percentage of high level clouds (PCLDH), the dominant of the
 904 three cloud types (high, medium, low) in Table 2. Here the distinction between the Arid-
 905 Venus simulations and the others is not consistent across the different rotation periods,
 906 suggesting that in some cases middle and/or low level clouds make important contribu-
 907 tions to SWCRF.

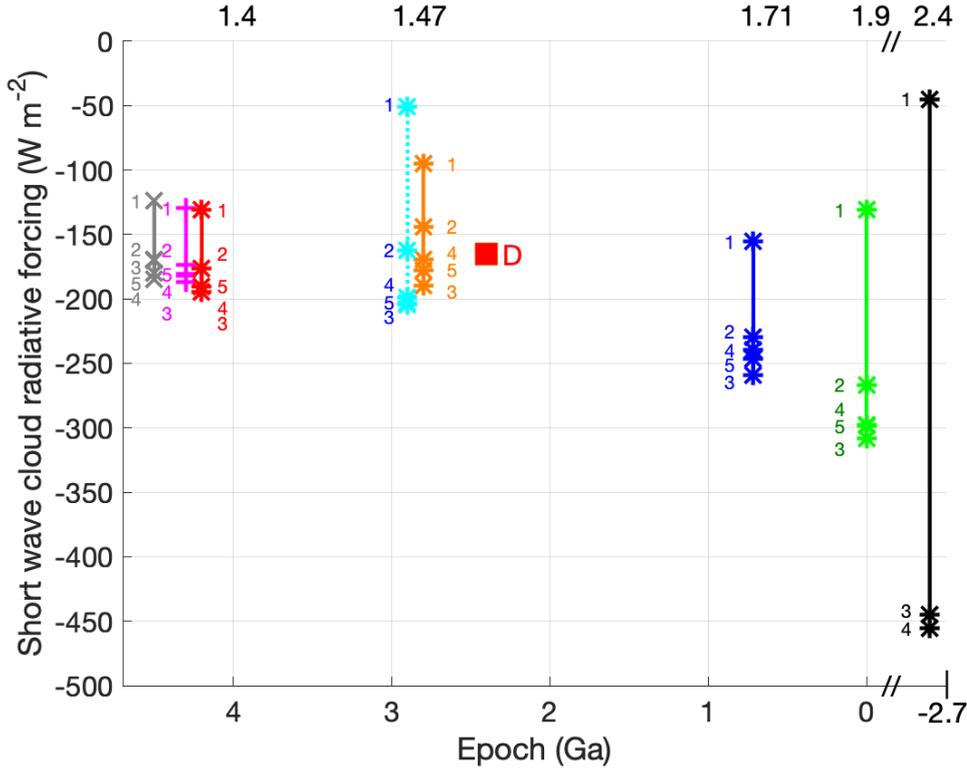


Figure 3. Shortwave cloud radiative forcing for the same evolutionary scenarios, defined as the difference between the solar radiation actually absorbed by the planet and how much would be absorbed if clouds were transparent. This is an estimate of how effective the clouds are at shielding the planet from the star’s intense radiation.

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7.2 2.9Ga

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Here we plot two different sets of simulations for N₂-dominated atmospheres: 1 bar (cyan; simulations 21-25) and 250mb (orange; simulations 26-30). In effect these portray representative possible atmospheres for an ancient Venus with liquid water that has evolved from an early CO₂-dominated atmosphere to a more Earth-like composition via the carbonate-silicate cycle feedback that is believed to regulate CO₂ on planets with liquid water. In both cases the Aqua-158m simulations have the highest mean surface temperatures with the Arid-Venus a close second, but all 10 simulations have moderate surface temperatures fairly similar to modern Earth. However as for simulations 6-20 the shortwave cloud radiative forcing is again the smallest for the Arid-Venus simulations (Figure 3) while also having less high cloud in (Figure 4) than the simulations with more surface water. Unsurprisingly, the thin 250mb atmospheres (simulations 26-30) have cooler surface temperatures in Figure 2. Simulations 27 & 28 have lower mean surface temperatures than modern Earth. The surface temperature field for simulation 28 is plotted in Figure 5 for reference. It exhibits fairly uniformly warm oceans, a signature of slowly rotating planets. Continental temperatures are cooler, slightly below freezing on average, due to nighttime cooling that offsets daytime warming. We also plot Simulation D from Paper I¹⁰ which is an N₂-dominated atmosphere, but is otherwise similar to ID 8 (a CO₂ domi-

¹⁰ The other 3 simulations from Paper I have similar values to their corresponding simulations herein.

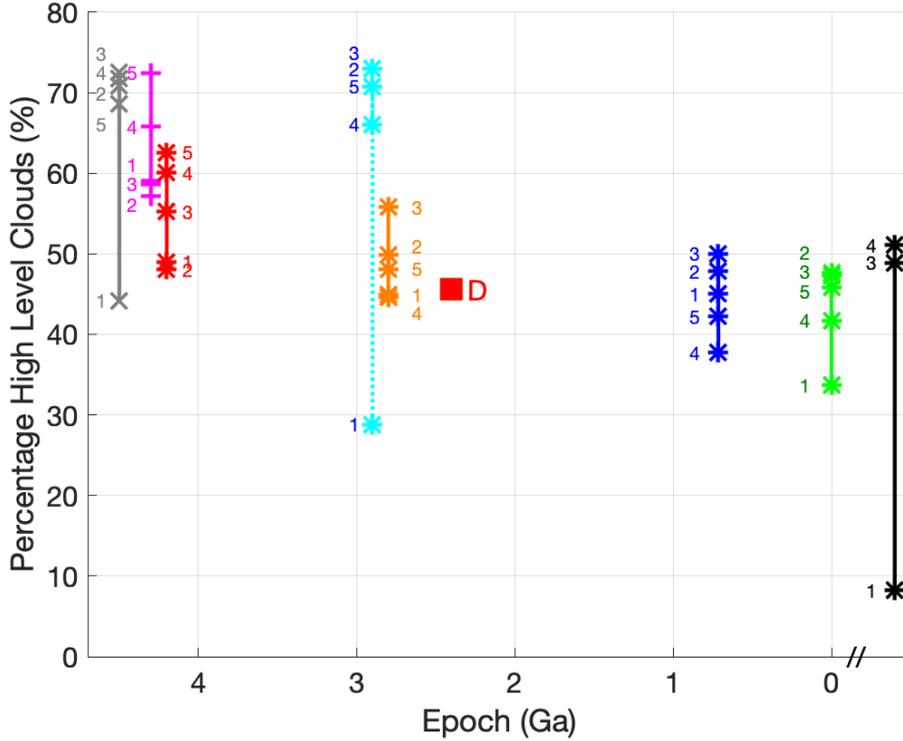


Figure 4. Percentage areal coverage of high level clouds (PCLDH). In Way et al. (2018) it was shown that PCLDH plays a key role in the cloud albedo feedback for slow rotators.

926 nated atmosphere) in Tables 1 and 2. It has a lower mean surface temperature than ID
 927 8 as expected, but is significantly higher than the other simulations with larger rotation
 928 periods (ID=21–30) at 2.9Ga. It has less short wave cloud radiative forcing (Figure 3)
 929 and lower percentage of high level clouds (Figure 4) compared to the other 310m-Venus
 930 simulations at 2.9Ga. This is expected given its faster rotation period, stronger Corio-
 931 lis force, and less contiguous clouds at the substellar point as discussed in Paper I.

932 **7.3 0.715Ga**

933 This epoch captures a possible final habitable phase on Venus, if the thick CO₂ at-
 934 mosphere we see today was created by volcanic emissions during the global resurfacing
 935 event(s). The spread in surface temperatures between simulations remains about the same
 936 as in previous epochs, but for all surface types the temperature is warmer than at 2.9
 937 Ga because of the brighter Sun. Again, the Aqua-158m is has the highest surface tem-
 938 peratures with the Arid-Venus close behind as in the 2.9Ga epoch. The SWCRF is some-
 939 what larger in general, due to both the stronger insolation and slightly reduced high cloud,
 940 but again the Arid-Venus has the smaller effect. The spread in high level clouds has shrunk
 941 considerably from the 1 bar simulations at 2.9Ga.

942 **7.4 Present Day**

943 This suite of simulations at Venus’ present day insolation are designed to demon-
 944 strate that even under today’s Sun the slow rotation cloud feedback effect would have
 945 remained strong as Venus’ atmospheric pressure and composition remain unchanged. This

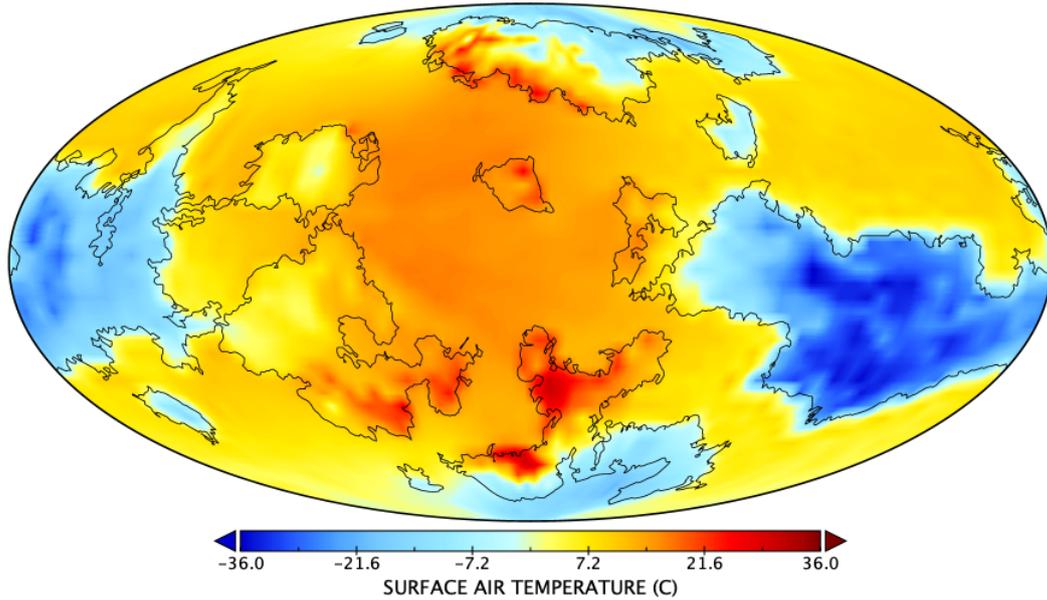
Simulation 28: 310m-Venus : 2.9Ga : -243X : 250mb : N₂ dominated

Figure 5. Simulation 28: mean surface temperature over 1/6th of a diurnal cycle. The sub-stellar point is centered over the middle of the plot.

946 points to the idea that it was not an increase in insolation that drastically changed Venus'
 947 clement climate of earlier epochs, but rather something else, which we speculate to be
 948 multiple/simultaneous large igneous provinces. The Arid-Venus simulations again have
 949 the highest temperatures and corresponding smallest SWCRF. This is more along lines
 950 of what we saw with the simulations at 4.2Ga, with climate forcing by a stronger Sun
 951 replacing climate forcing by a thicker greenhouse gas atmosphere as the primary reason
 952 for a warm climate.

953 7.5 Future

954 Our last set of simulations at insolation values 2.4 times that of present day Earth
 955 are meant to show how long a temperate Venus-like world could have remained habit-
 956 able for a given surface type. Our 10m-Venus and 310m-Earth simulations are not in equi-
 957 librium and so are not plotted. The Arid-Venus simulation is at nearly 100° Celsius. It
 958 appears to be approaching radiative equilibrium, but the simulation crashed after 20 years
 959 so it is difficult to be certain. At this point the cloud/albedo feedback for the Arid-Venus
 960 case has decreased to Earth-like values (the SWCRF is a mere -50 W m^{-2}). This simu-
 961 lation has the lowest value of PCLDH, which makes it hard to counter the increased
 962 insolation at this time in order to keep mean surface temperatures below the boiling point
 963 of water.

964 7.6 General Trends

965 A few relatively consistent trends are apparent from our simulations. First, the Arid-
 966 Venus simulations tend to have the highest surface temperatures, smallest values of SWCRF
 967 and lowest percentages of PCLDH. In many cases the 10m-Venus simulations are next,
 968 but not always. This may point to the fact that even with 10m of available water the

969 cloud/albedo feedback is generally effective at shielding this slowly rotating world from
 970 the intense solar radiation at all epochs when considering what modern Earth receives.
 971 The simulations with generally higher water availability and similar percentages of land-
 972 to-sea (310m-Venus and 310m-Earth) tend to cluster together in Figures 2,3,4. The 158m-
 973 Aqua simulations seem to float in between, perhaps because of the lower surface albedo
 974 in combination with the cloud albedo feedback.

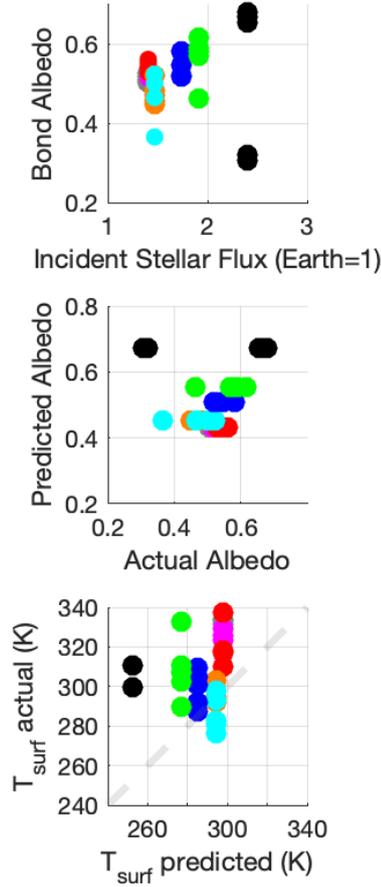


Figure 6. Upper panel: Bond albedo vs. incident solar flux for the planets in Figure 2. Middle panel: Predicted versus actual Bond albedos for the same set of planets after Del Genio, Kiang, et al. (2019). Lower panel: Predicted vs. observed surface temperatures after Del Genio, Kiang, et al. (2019).

975 Even without a transition to a runaway greenhouse, prior water loss due to the
 976 onset of a “moist greenhouse” state may have been important to Venus’ evolution. A num-
 977 ber of simulations in Table 2 contain stratospheric water concentrations (Q_{top}) greater
 978 than $3 \times 10^{-3} \text{ kg kg}^{-1}$, the traditional Kasting et al. (1993) limit for onset of the moist
 979 greenhouse. However, recent work by Chen et al. (2019) for M-star planets has demon-
 980 strated that previous work may have overestimated water loss rates. Hence we should
 981 exercise more caution in using $3 \times 10^{-3} \text{ kg kg}^{-1}$ as a hard value for the moist greenhouse
 982 until similar models are applied to G-star planets. Column Q_{surf} is a check on the amount

983 of water vapor at the surface of the model. ROCKE-3D runs with a fixed molecular mass
 984 at model start and ignores the spatially/temporally variable mass of water in calculat-
 985 ing pressure gradients, so it is important to keep track of whether water becomes a non-
 986 negligible fraction of atmospheric mass (e.g., 20% of the total or more) as the dynam-
 987 ics in the model will begin to be outside an acceptable range. Only in simulation 45 does
 988 this value go over the 20% limit.

989 Figure 6 shows calculations for what exoplanet astronomers might find for a popu-
 990 lation of “exo-Venuses,” some of them habitable and some not, in future observations.
 991 We use an ensemble of ROCKE-3D simulations of a variety of rocky planet types from
 992 which predictors for Bond albedo and surface temperature have been derived using in-
 993 solation and star temperature as inputs (Del Genio, Kiang, et al., 2019, hereafter DG19).
 994 Figure 6 applies the predictor to our Venus evolutionary scenarios to determine the pre-
 995 dictability of albedo and surface temperature. In general Bond albedo increases with in-
 996 solation in the Venus simulations (upper panel), the exceptions being 4 of the Arid-Venus
 997 cases with limited surface water, fewer clouds and thus lower albedos than our other simu-
 998 lations. The DG19 predictor (middle panel) works well for all but these 4 cases, since
 999 it predicts a high cloud-controlled albedo for the wetter planets that have more and/or
 1000 thicker clouds than others. For surface temperature (bottom panel), the predictor tends
 1001 to underestimate the actual temperatures by roughly 20° or less in most cases, but by
 1002 up to 50° for the hotter, drier, marginally habitable Arid-Venus cases.

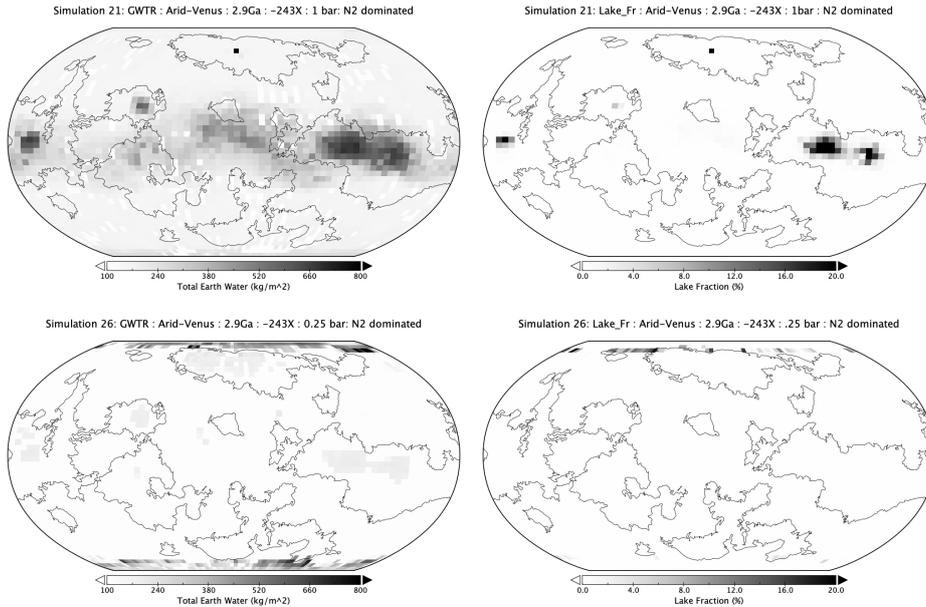


Figure 7. GWTR left panels, LakeFR right panels for Top to Bottom: Simulation 21 and 26 (Arid-Venus).

1003 Figure 7 shows (left panels) the vertically integrated soil moisture and (right panels)
 1004 lake fraction for two of our Arid-Venus simulations at 2.9 Ga with Earth-like atmo-
 1005 spheres: Experiment 21 (1 bar, top panels) and Experiment 26 (250 mb, bottom pan-
 1006 els). The Arid-Venus cases are of particular interest because they are initialized with a
 1007 spatially uniform subsurface soil water reservoir and no standing water bodies, and they
 1008 then equilibrate to a heterogeneous distribution of surface and subsurface water depend-
 1009 ing on the climate and circulation and thus the local precipitation-evaporation compe-
 1010 tition. The 1 bar atmosphere is typical of the behavior of most of the experiments in Ta-

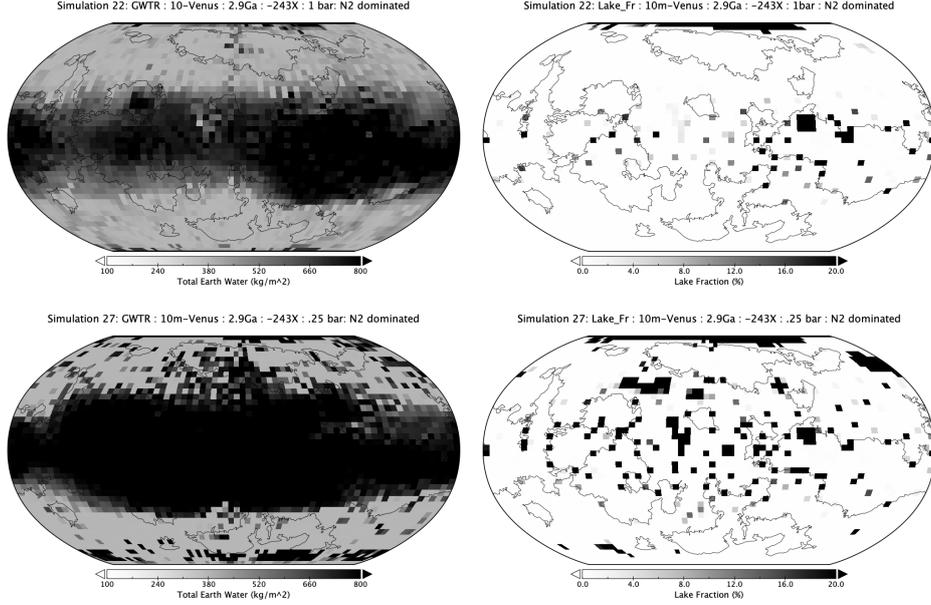


Figure 8. GWTR left panels, LakeFR right panels for Top to Bottom: Simulation 22 and 27 (10m-Venus).

1011 ble 1: In equilibrium, subsurface water collects primarily in the equatorial region where
 1012 rising motion and precipitation is prevalent during the daytime, and especially in high-
 1013 land regions such as Aphrodite Terra. Lakes (which are not present in the initial condi-
 1014 tion) also form preferentially over the equatorial highlands. The 250 mbar simulation
 1015 is an outlier, with subsurface water and lakes arising primarily at high latitudes. This
 1016 is reminiscent of what is observed for the methane-ethane lakes on Titan, which Mitchell
 1017 (2008) is able to reproduce in a GCM when a limited subsurface methane reservoir is
 1018 assumed.

1019 Figure 8 shows the same quantities for the analogous 10-m Venus simulations (Ex-
 1020 periments 22 and 27). These differ from the Arid-Venus cases not only because the planet
 1021 contains more water, much of it in surface lakes rather than subsurface soil moisture, but
 1022 also because the lakes fill the lowlands at the start of each simulation rather than be-
 1023 ing distributed uniformly across the planet. With a larger water reservoir than that for
 1024 the Arid-Venus planets, soil moisture collects throughout the tropics in the equilibrated
 1025 climate, but still with a slight preference for the highland regions even though there is
 1026 no standing water in the highlands in the initial condition. But unlike the Arid-Venus
 1027 planets, soil moisture also collects at the poles, both for the 1 bar and the 250 mb at-
 1028 mosphere planets. Likewise, lakes in both simulations form in both the tropics and po-
 1029 lar region, more so over the highlands for the 1 bar atmosphere but fairly uniformly dis-
 1030 tributed in longitude for the 250 mb atmosphere.

1031 8 Conclusion

1032 Whether Venus' original water survived its initial MO stage, or whether significant
 1033 water was delivered afterwards, is unknown. It is therefore worth having a theoretical
 1034 framework that considers the possibility of an early habitable Venus as a starting point
 1035 for designing future observing strategies that might shed light on Venus' past. In this

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spirit, we envision the following possible climatic evolution for Venus and provide Figure 9 as a guide:

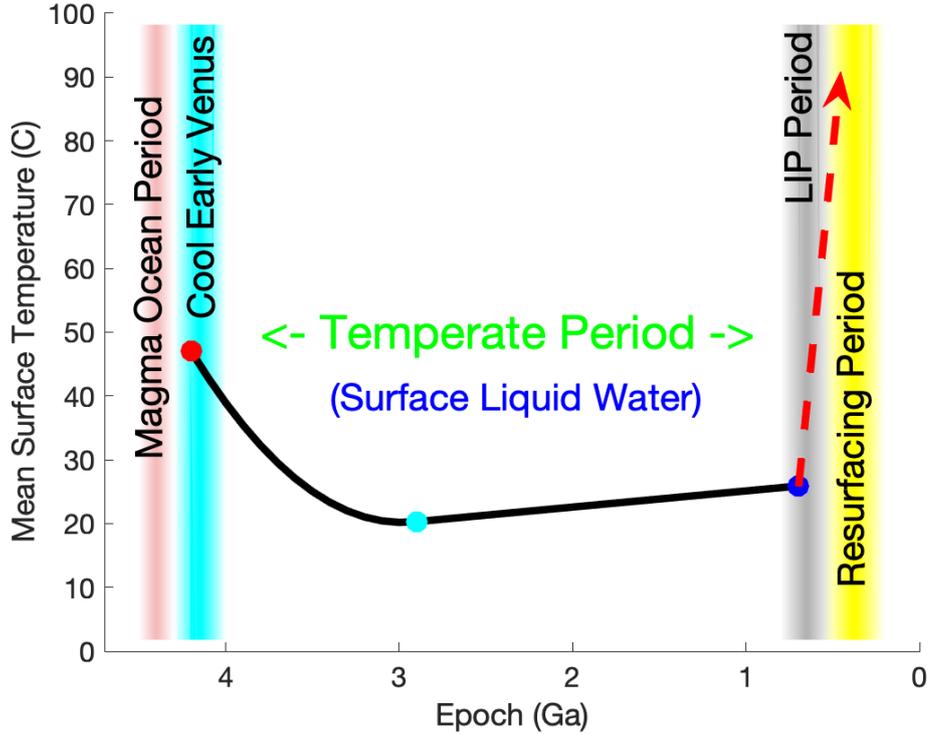


Figure 9. Graphical representation of Venus' possible climate history. The three data points represent the 1 bar atmospheres modeled at those points in time. The red dashed arrow to the right represents the transition to a moist/runaway greenhouse and eventually to Venus' present day surface temperature and atmospheric density.

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1.) Toward the end of the accretion period (~ 4.2 Ga) Venus would have cooled rapidly as did Earth, as shown in the work of J. W. Valley et al. (2002). This would allow surface water to condense and early oceans to form. Early oceans in turn could create significant tidal dissipation that would spin down Venus' rotation rate on a relatively short time scale as shown in work by (Green et al., 2019) and described in Section 5 above. Solid body dissipation may have also been effective, see Section 5. Slow rotation combined with an early ocean would provide the necessary ingredients for a dayside cloud deck to emerge, shielding the planet from high insolation and allowing at least some of the initial surface water to survive despite the planet being well inside the conventional inner edge of the habitable zone, as shown in the work of Yang et al. (2014); Way et al. (2018).

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2.) The carbonate-silicate cycle in concert with interior volatile cycling would allow CO_2 draw-down while N_2 was outgassed, eventually reaching a balance producing an N_2 -dominated atmosphere with trace amounts of CO_2 over gigayears with pressures ranging from several bars to hundreds of millibars.

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3.) We propose that any stable Venusian climate period came to an end around 700Ma, as evidenced by the age of the surface from crater counts (McKinnon et al., 1997). We suggest that the ignition of multiple large igneous provinces (LIPs) became active

1056 around that time (over a period of 10s or 100s of millions of years). This would not have
 1057 been the global LIP as proposed by (Lpez et al., 1998) as it is not necessary and seems
 1058 to have little support in the community. It is likely that the eruption of LIPs through-
 1059 out Earth’s history (Ernst, 2014; Ernst et al., 2019) is a random stochastic process. This
 1060 may imply that multiple large scale LIPs have not occurred simultaneously on Earth by
 1061 purely random chance, which is fortuitous for life as we know it today. Venus may not
 1062 have been as fortunate. Unfortunately, little is known about Venus’ interior structure
 1063 today, much less its initial state and subsequent evolution, so the question remains as
 1064 to whether deterministic evolutionary processes in the interiors of Venus-like planets will
 1065 inevitably lead to catastrophic changes and uninhabitable end states.

1066 4.) Multiple large scale LIPs would have warmed the world markedly via the re-
 1067 lease of large amounts of CO₂ via one or more mechanisms and its greenhouse effect on
 1068 the climate (e.g., Ogden & Sleep, 2012) over 10s or 100s of millions of years.

1069 5.) This warming could have hastened a movement toward the onset of a moist (Kasting
 1070 et al., 1993) and possibly a runaway greenhouse state in which much of the surface wa-
 1071 ter was lost via photodissociation accompanied by hydrogen escape and an oxidized
 1072 surface. Recall that present day Venus D/H measurements (if they are accurate) imply
 1073 .6 to 16% of Earth’s present day surficial water stores (Donahue et al., 1997). Hence the
 1074 timescale of total loss would be at least an order of magnitude faster than that described
 1075 in Kasting et al. (1993), although there is still uncertainty about the stratospheric con-
 1076 ditions under which a moist greenhouse occurs (e.g., Chen et al., 2019) and when a run-
 1077 away greenhouse is achieved (e.g., Kasting & Ackerman, 1986; Goldblatt et al., 2013; Ramirez,
 1078 Kopparapu, Lindner, & Kasting, 2014). Work by Grinspoon (1993) on the D/H ratio
 1079 may also support this hypothesis as they state: “Thus (D/H)_{obs} may be the isotopic sig-
 1080 nature of a catastrophic resurfacing in the past 0.5–1 Gyr.”

1081 6.) A major issue with any proposed evolutionary scenario with long lived surface
 1082 water reservoirs then arises: what happened to the large quantities of oxygen expected
 1083 to be left over from a Venusian ocean? This is the oxygen that would have remained in
 1084 the atmosphere after the photo-dissociation of H₂O and the loss of the hydrogen (Watson
 1085 et al., 1981), but not oxygen, via atmospheric escape. In fact large quantities of abiot-
 1086 ically produced O₂ (100s to 1000s of bar) left over in such a scenario has been proposed
 1087 as an observational signature in exoplanetary atmospheres on planets that have lost their
 1088 oceans (Luger & Barnes, 2015). For our Arid-Venus scenario it may be possible to lose
 1089 much of the oxygen via a combination of atmospheric escape (Persson et al., 2018) and
 1090 absorption by a surface like that of present day Venus (e.g., M. Gilmore et al., 2017). How-
 1091 ever, recently submitted work by Persson et al. (2020) demonstrates that 0.3 m of a global
 1092 equivalent layer of water could have been lost via atmospheric escape alone in the past
 1093 ~4Ga. Hence the 0.2 m global equivalent layer of water in our Arid-Venus scenario fits
 1094 within this framework. Yet work by Persson et al. (2018); Masunaga et al. (2019); Pers-
 1095 son et al. (2020) and their estimates for O+ escape rates shows that atmospheric escape
 1096 alone is not sufficient to remove larger reservoirs of oxygen left over from the oceans in
 1097 our other non-Arid-Venus simulations. Some caveats go with this work in that the Venus
 1098 atmosphere simulated for our temperate period¹¹ (N₂ dominated with 400ppmv CO₂ and
 1099 1ppmv CH₄) is very different from that of modern Venus with thermospheric and exo-
 1100 spheric temperatures likely to be distinct and possibly affecting escape rates (Airapetian
 1101 et al., 2017). On the other hand current estimates of atmospheric escape rates for Earth
 1102 & Venus are very similar (e.g. Gunell et al., 2018; Airapetian et al., 2019), which may
 1103 give us some confidence in extrapolating to our temperate Venus scenario.

1104 We propose that the large-scale resurfacing evident on Venus today, which took place
 1105 over 100s of millions of years, is a possible effective answer. It must be noted that this

¹¹ More akin to an Archean Earth atmosphere than modern day Earth or Venus.

would be separate from the earlier (in geological time) LIP scenario above. Since the Magellan mission it has been known that 80% of the surface of Venus is relatively young, with estimates ranging from 300-700 Myr old as mentioned in Section 4. These newly exposed basalts would be the ideal sink for large quantities of oxygen (possibly 100s of bars) over 100s of millions of years. According to (Lécuyer et al., 2000) Venus would need to oxydize a rock layer ~ 50 km deep to absorb an Earth's worth of ocean, and they propose a mechanism for doing so while citing the earlier work of Pieters et al. (1986). Note that none of the oceans proposed herein are close to an Earth's ocean in volume, hence the number could be much smaller. For example, work by Grinspoon (1993) and J. W. Head et al. (1992) note that the volume of magma necessary to cover all pre-existing craters is ~ 10 km, and that would be sufficient for the volume of oceans proposed in our models. Some fraction of the oxygen may actually be deep within Venus lithosphere and possibly even within its mantle. This may be consistent with coronae-related subduction hypotheses (Sandwell & Schubert, 1992; Davaille et al., 2017) and other ideas about downwelling-associated highlands (e.g. J. W. Head et al., 1992, see Fig 2), where thicker crustal regions may exhibit orogenesis (e.g., Head et al., 1990) and sinking of parts of the lithosphere into the mantle (e.g., Lenardic et al., 1991; Bindschadler et al., 1992).

7.) The loss of water would in turn change the planet from an initial subductive or mobile plate tectonic mode to more of a stagnant lid mode (as on present day Venus & Mars) since it is currently believed that water plays a key role in plate tectonics on Earth (e.g., Grove et al., 2012; Lécuyer, 2014). This scenario fits in very nicely with the recent work of (Weller & Kiefer, 2019) who give a timescale of order 1Gyr for the transition from a mobile to a stagnant lid mode on Venus. Without a mechanism to efficiently cycle volatiles in a stagnant lid mode (e.g., Tosi et al., 2017; Höning et al., 2019), outgassing would have continued without the major weathering and subduction surface sinks that operate on Earth, hence CO_2 and N_2 would build up over time to reach the levels we see on Venus today. Some studies have also shown that even in a stagnant lid mode it is possible to cycle volatiles, possibly up to gigayears in time (e.g., Foley & Smye, 2018; Godolt et al., 2019), but these mechanisms depend on the initial CO_2 budget and the retention of at least some water after cooldown.

8.) This stagnant lid mode may then allow very large mantle upwelling and/or downwelling centers that would produce some of the features we see on Venus' surface today produced over hundreds of millions of years, as described most recently in the works of e.g. Rolf et al. (2018); Weller and Kiefer (2019).

Our scenario can also fit within the Fortunian, Guineverian & Atlian periods proposed in the works of Ivanov and Head (2015) and Airey et al. (2017), as it is not possible to constrain the start of the LIP period we propose with the data we have today. Our LIP period could easily have concluded in the pre-Fortunian or Fortunian period ~ 1.5 Ga.

One of the remaining quandaries in our hypothesis is the fact that the 92 bar atmosphere we see on Venus today must go back at least as far as the age of the visible surface because there are fewer small craters (< 35 km in diameter) to be seen in the Magellan data (Schaber et al., 1992, see Figure 2). Certainly smaller craters would be visible if the atmosphere had been significantly thinner in the lifetime of the observed surface when atmospheric filtering of smaller impactors would have been less prevalent.

For example, assuming the tesserae are the oldest stratigraphic units why are there no small craters present if the present day atmosphere is not a primordial feature from many eons ago? One resolution to this problem could be that the tesserae are not as old as we think they are, and until we date these units and the basaltic flats we really won't know. Secondly, as mentioned above, there is the possibility that there have been multiple resurfacing events and the tesserae are left-over from one of the previous events. Neither is a terribly optimistic scenario if one is hoping that some of tesserae may be rem-

1158 nant crust from a period of hosting surface water. Finally, a large impactor may be the
 1159 cause of the catastrophic climate change we propose. This could have also played a role
 1160 in resetting the clock on the surface of Venus reconciling the lack of small craters. In this
 1161 scenario the LIP hypothesis plays a partial role in the evolution of Venus’ climate. This
 1162 would be similar to what we have seen in the on-going debate regarding the K-Pg pe-
 1163 riod on Earth (e.g. Hull et al., 2020; Schoene et al., 2019; Sprain et al., 2019). Such an
 1164 impactor’s imprint would have long been lost due to Venus’ relatively young surface. Our
 1165 comments about impactors in Section 4 apply here as well.

1166 Clearly a great deal more modeling work and more observations are required to con-
 1167 firm or refute this hypothesis. Did Venus follow the ‘canonical’ path with Earth-like con-
 1168 ditions in it’s early history and then experience a moist-runaway greenhouse due to in-
 1169 creasing solar insolation? Did it experience a longer period of habitability throughout
 1170 most of its history, with its demise and present hothouse state the consequence of a se-
 1171 ries of LIP events releasing CO₂ bound up in the crust as on Earth, and/or released from
 1172 the deep interior where CO₂ is more easily sequestered (e.g., Kuramoto & Matsui, 1996)?
 1173 Or did it become bone dry in an extended magma ocean phase in the first 100*Myr*, as
 1174 described in Hamano et al. (2013) for Type II planets?

1175 We believe the only scenario we can begin to rule out with the present work is the
 1176 ‘canonical path’ since there is no evidence that an early period of habitability would have
 1177 been affected by increasing solar luminosity in the first billion years. In essence, if Venus
 1178 had habitable surface conditions with surface liquid water ~ 4 Ga then the same cloud
 1179 albedo effect that allows such a scenario would continue for eons. On the other hand we
 1180 will not be able to distinguish between the two remaining scenarios until we return to
 1181 Venus to make proper noble gas and other elemental and isotopic measurements at the
 1182 surface (Baines et al., 2013) and better constrain escape processes at the top of the at-
 1183 mosphere through time. The latter will also rely upon how such gases escape from present
 1184 day Earth given the possibility that Venus may have had a magnetic field in previous
 1185 epochs, even if it is not clear how important the magnetic field is to escape processes in
 1186 general (Gunell et al., 2018). Likewise, whether the actual evolution of the one Venus
 1187 we can visit is the ultimate fate of all highly irradiated rocky planets or an accident of
 1188 an evolutionary path that might have proceeded differently in other circumstances (e.g.
 1189 Lenardic et al., 2016) is not known. The stakes are high for answering this question, since
 1190 many exoplanets have been discovered in the “Venus zone” just inside the traditional
 1191 inner edge of the habitable zones of other stars (Kane et al., 2014). Efforts to simulta-
 1192 neously characterize the CO₂ concentrations and climates of a number of these exoplan-
 1193 ets, combined with a focused observational strategy for unveiling the history of the “ex-
 1194 oplanet next door” to Earth in our own solar system (Kane et al., 2019), will be our best
 1195 chance to understand whether the envelope for habitability and the emergence of life is
 1196 much broader than usually assumed.

Table 2. Results

ID ^a	Runtime years	Temp ^b C	Balance ^c W m ⁻²	Q _{top} ^d kg/kg	Q _{surf} ^e %	Albedo Planetary	Albedo Surface	Clouds High	Clouds Medium	Clouds Low
01	71	262	0.01	1.36e-05	0.08	54	29	54	5	0
02	111	151	27.21	2.67e-05	3.74	54	18	33	17	33
03	67	121	21.31	4.50e-04	7.87	52	11	45	23	37
04	52	120	51.28	1.74e-04	10.01	44	7	36	17	51
05	56	123	36.27	4.28e-04	9.16	49	10	46	24	44
06/01	100	96	0.06	1.73e-03	1.65	51	29	44	2	0
07/02	100	76	0.41	9.34e-03	7.70	53	16	71	32	21
08/03	53	61	5.92	6.49e-03	7.50	50	10	72	32	47
09/04	100	59	-0.48	6.23e-03	6.95	52	7	73	35	62
10/05	60	60	1.90	5.46e-03	7.19	52	9	69	37	53
11/01	200	73	0.05	9.03e-04	1.70	52	29	59	4	1
12/02	500	50	0.04	5.94e-04	2.07	55	16	57	10	10
13/03	200	45	0.87	1.56e-03	3.15	54	10	59	18	43
14/04	156	53	0.11	3.47e-03	4.81	51	7	66	25	60
15/05	200	56	0.44	4.58e-03	5.65	52	9	72	28	49
16/01	300	64	0.01	8.34e-04	0.80	53	28	49	4	1
17/02	500	44	0.06	5.68e-04	1.40	56	16	48	9	8
18/03	1000	37	0.13	8.18e-04	2.07	56	10	55	15	38
19/04	500	44	-0.50	1.59e-03	3.01	54	7	60	17	56
20/05	500	45	0.23	1.88e-03	3.15	54	9	63	19	44
21/01	500	22	0.02	2.52e-05	0.36	46	28	45	6	4
22/02	3000	21	-0.04	3.08e-05	0.61	47	17	50	10	12
23/03	1000	10	-0.05	2.53e-06	0.70	52	10	56	20	48
24/04	500	30	-0.12	3.51e-05	2.32	45	6	45	14	37
25/05	1000	19	0.05	5.87e-06	1.24	48	9	48	22	39
26/01	300	20	0.11	5.94e-03	0.53	37	29	29	5	9
27/02	1000	8	-0.14	9.98e-03	1.26	50	20	73	17	27
28/03	1000	3	-0.02	6.15e-03	1.94	52	13	73	8	13
29/04	1000	25	0.34	2.69e-02	6.39	47	6	66	1	0
30/05	500	10	0.08	8.58e-03	2.76	50	10	71	7	10
31/01	200	32	-0.03	1.12e-04	0.63	52	28	45	7	4
32/02	297	19	0.02	8.32e-05	0.87	2	1	48	20	26
33/03	1000	15	-0.03	1.18e-05	0.95	58	10	50	28	47
34/04	500	36	-0.03	6.41e-04	3.32	52	7	38	17	42
35/05	500	28	0.27	1.11e-04	2.04	55	9	42	26	40
36/01	50	60	-0.09	3.05e-03	0.58	46	29	34	2	1
37/02	2000	29	-0.01	4.33e-04	1.17	59	17	48	16	23
38/03	1000	16	0.12	3.52e-05	1.08	62	10	47	33	47
39/04	500	38	-0.07	1.37e-03	3.57	57	7	42	21	42
40/05	1000	34	0.35	1.10e-03	2.92	58	9	46	24	41
41/01	20	99	0.52	3.13e-03	0.43	32	29	8	0	0
42/02	8	288	90.21	1.00e-01	11.71	31	17	31	0	0
43/03	1000	26	0.01	3.35e-03	1.99	68	11	49	33	54
44/04	500	38	0.23	5.52e-03	3.75	67	8	51	44	54
45/05	35	83	32.64	1.05e-01	30.36	66	10	89	19	16
D	2000	56	0.19	5.31e-03	8.97	44	10	46	39	45

^aID: The colored numbers correspond to those in Figure 2.

^bTemp: Surface temperature in Celsius.

^cBalance: These numbers come from 50 year averages unless the Runtime (Column 2) is less than 150 years, then the average is 10 years.

^dSpecific humidity in top layer of the atmosphere.

^eSurface humidity as percentage of atmosphere.

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Appendix A Energy balance and temperature

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Different simulations reach radiative balance sooner than others, while some never reach it at all. Herein we plot the energy balance (in units of W m⁻²) and surface temperature (in Celsius) as a function of simulation year. This should allow the reader to have a better grasp of which simulations are appropriate for a given interest.

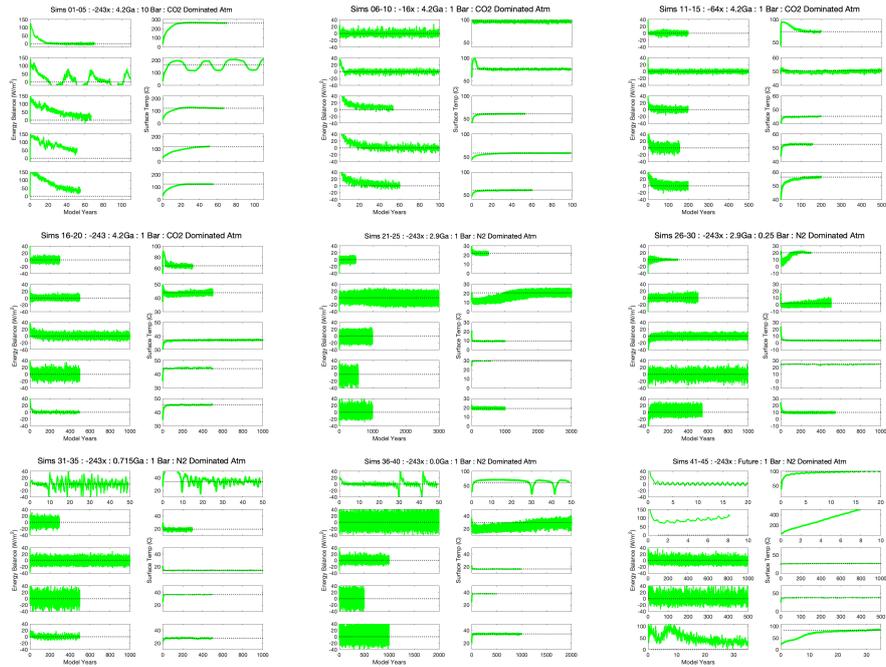


Figure A1. Energy Balance (also called Net Radiative Balance) in the left columns and surface temperature in the right columns as a function of simulation year for all simulations in this study. Note that not all limits on the x or y axes are the same.

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https://portal.nccs.nasa.gov/GISS_modelE/ROCKE-3D/publication-supplements/

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