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

M.J. Way[1,2,3], and Anthony D. Del Genio[1]

[1]NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY, 10025, USA
[2]GSFC Sellers Exoplanet Environments Collaboration
[3]Theoretical Astrophysics, Department of Physics and Astronomy, Uppsala University, Uppsala, SE-75120, Sweden

Key Points:

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

Corresponding author: M.J. Way, `Michael.J.Way@nasa.gov`

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. This leads to the conclusion that Venus' present state is the result of a runaway greenhouse from a gradually warming sun since its formation. 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 because of its closer proximity to the Sun. This would differ from Earth's evolution since Earth's magma ocean lifetime was probably around 1 million years. Venus' long lived steam atmosphere would allow sufficient time to dissociate most of the water vapor, allow significant hydrogen escape and oxidize the magma ocean. Maybe the high deuterium to hydrogen ratio is from this period. However, a dearth of observational data due to a lack of missions to Venus makes it impossible to choose between these two scenarios. Using a general circulation model we demonstrate the viability of the optimistic scenario using the few observational constraints available. 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 with 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 Venus' global resurfacing 100s of millions of years ago played a key role in ending the clement period in its history.

1 Introduction

The case for the early 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; D. H. 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 for characterization of the atmospheres of these planets. Hence, what appears to be a modern Venus-like world close to its parent star might host surface liquid water. We refer to such habitable worlds as residing in an "Optimistic Venus Zone," a subset of the planets in the "Venus Zone" described in Kane et al. (2014).

There are three primary requirements for the early habitability of Venus. The first is that temperatures were low enough that liquid water was capable of condensing on the surface of Venus. The second is that Venus had a sufficient inventory of water to create the conditions believed necessary for the rise of life on terrestrial worlds (e.g., Brack et al., 2010). Third, volatile cycling and a geologically active surface must exist to regulate the climate as possibly supported by the work of Noack et al. (2012). For surficial water reservoirs most research has focused on the poorly constrained measurement of the D/H ratio of $\sim 150 \pm 30$ (times Earth's value) by the Pioneer Venus Mission[1] (Donahue et al., 1982, 1997). A number of other ground based measurements have been made (De Bergh et al., 1991; Marcq, 2006; Bjoraker et al., 1992; Fedorova et al., 2008) that have generally revealed values of D/H greater than 100. For a recent review of D/H measurements of Venus see Section 6.3 of Marcq et al. (2017). We review the work of authors who have considered Venus' climate evolution below.

The first simple gray radiative transfer calculations of Venus' climate history suggested an early runaway greenhouse effect (e.g., Ingersoll, 1969; Rasool & de Bergh, 1970). Any water would have remained in vapor form throughout Venus' early history until its loss to space via photodissociation processes (Goody & Walker, 1972; Walker, 1975). CO_2 would continue to be outgassed and would accumulate (offset by atmospheric loss over the last 4.5Gyr) to the values we see today.

Pollack (1971) used a similar model but with non-gray radiative transfer. This was probably the first work to show that Venus could have hosted liquid water on its surface in its early history, but they also demonstrated that a runaway greenhouse was possible as well. The difference between the two outcomes was *mostly* due to to the specified cloud cover and water vapor content of the atmosphere. With 50% cloud fraction the result was usually a runaway greenhouse. For an N_2 dominated atmosphere with a modern Earth water vapor profile, 100% cloud cover, and a 30% less luminous sun (akin to ∼4.5Ga) he achieved surface temperatures ∼300K. These purely radiative models did not include convection, which would limit the water vapor mixing ratio by precipitation and limit the lapse rate of temperature to the moist adiabatic value (Rampino & Caldeira, 1994) and lessen the strength of the greenhouse effect to some degree. Likewise, they did not include an atmospheric general circulation that would determine the cloud fraction self-consistently. Donahue and Pollack (1983) replicated some aspects of the Pollack (1971) work and again showed that clement conditions were possible in Venus' early history.

Kasting et al. (1984) used a 1-D radiative-convective model to demonstrate that a planet with an insolation S0X=1.45 times that of modern Earth (1973 W m^2 ∼ 3.8Gya at Venus' orbit) would have temperatures $\sim 100°$ C for a 2 bar N_2 H_2O atmosphere. This atmosphere contained a wet stratosphere, and thus photodissociation of H_2O and subsequent escape of hydrogen (e.g., Goody & Walker, 1972) could explain the long-term loss of Venus' primordial ocean and its present dry conditions. In a subsequent study Kasting (1988) claimed that clouds would cool the atmosphere enough to keep it in a moist greenhouse state, rather than the runaway state. At the same time the Kasting (1988) surface temperature for his "Early Venus" (Figure 7) cloud-free model was ∼500K and hovered just at the margin of the moist vs. runaway greenhouse states. Thus it was clear early on that maintaining liquid water on ancient Venus required high fractional cloud cover, but whether physical mechanisms exist to produce these cloudy conditions was not addressed.

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

Grinspoon and Bullock, in a number of abstracts (e.g., D. H. Grinspoon & Bullock, 2003; D. Grinspoon, 2008), described a Venus climate evolution scenario consistent with that described later in this paper. This work was never published, though, so the details of their calculations and the justifications for their conjectures are not documented.

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

A rationale for high albedo cloud cover on ancient Venus was first presented by Yang et al. (2014). Yang et al. (2014) was a large parameter study looking at the inner edge of the habitable zone around solar type stars using a modern GCM[2] with comprehensive atmospheric physics but a thermodynamic ocean. In essence they stepped the sidereal rotation rate of an Earth-like world from 1 to 256 sidereal days. At the same time they increased the insolation from that of modern Earth to as much as 2.6 times the modern Earth for their most slowly rotating world of 256 sidereal days period. One of their key conclusions was that the slowest rotators would have had a day-night general circulation that would generate an optically thick contiguous cloud bank in the substellar region. This cloud deck would greatly increase the planetary albedo, keeping the surface temperature moderate even for quite high values of insolation. These results were later confirmed with a completely different 3-D GCM with a fully-coupled dynamic ocean (Way et al., 2018). Yang et al. (2014) also included a simulation with modern 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, insolations 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

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

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 CO_2-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; K. Zahnle & Sleep, 2002; J. W. Valley et al., 2002; K. J. Zahnle, 2006; K. 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)[3]. 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 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 a "cool early Venus" hypothesis. In some ways, the prospects for this cool early Earth and Venus hypothesis have improved with increasing evidence that the impact of the late heavy bombardment (LHB) on Earth's accretional history may have been overestimated. The intensity of the LHB 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. Recent work by S. J. Mojzsis et al. (2019) has demonstrated that the LHB was either a very minor event or never took place and that surface temperatures continued their downward trend from the cool early Earth period (see S. J. Mojzsis et al. (2019) Figure 1). 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." Hence, the work of S. J. Mojzsis et al. (2019) demonstrates that the flux from the LHB was originally overestimated and that the cool early Earth continued through the originally proposed time period of the LHB from $\sim$ 3.8–4.1Ga. Hence we will begin our most ancient Venus simulations with CO_2 dominated atmospheres at $\sim$4.2Ga (during the J. W. Valley et al. (2002) cool early Earth period) that evolves over time to N_2 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). Regardless,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 CO_2 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 re-

[3] For Catling and Kasting (2017) see section 11.4

mains 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[4] Hence in this scenario a carbonate silicate cycle is hypothesized for Venus after the magma ocean phase and before its resurfacing period to keep CO_2 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; Avice 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 N_2 of factors of a few have relatively small net impacts on climate, primarily due to small decreases/increases in the pressure broadening of CO_2 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 CO_2 and N_2 inventories of Earth and Venus may be similar (Donahue & Pollack, 1983; Goldblatt et al., 2009) if Venus is more degassed than Earth as Donahue and Pollack (1983) speculated. Early work by Rasool and de Bergh (1970); Kasting (1988) estimated nearly as much CO_2 was locked up in carbonate rocks on Earth as exist in the atmosphere of Venus. Since there is no carbonate-silicate cycle active on Venus today most of the CO_2 that would otherwise be locked up in the interior is in the atmosphere, having degassed over the past several hundred million years (at least). As well, nearly 4 times as much N_2 is found in Venus' present day atmosphere as in Earth's when scaled by planetary mass. Earth's internal N_2 budget is estimated at $\sim 7 \pm 4$ times that of the atmospheric mass (Johnson & Goldblatt, 2015).

However, Argon (Ar) modeling studies (Kaula, 1999; ORourke & Korenaga, 2015) imply that Venus is less degassed than Earth, although see Donahue and Pollack (1983) and Halliday (2013) for alternative explanations for the current ^{40}Ar abundance difference between Earth & Venus. Watson et al. (2007) claims that ^{40}Ar is not a reliable indicator of degassing, although "the interpretation of their data is controversial" according to ORourke and Korenaga (2015). Halliday (2013) also mentions that Venus' radiogenic ^{40}Ar implies Venus is less degassed than Earth, but he notes that Venus' atmospheric non-radiogenic ^{36}Ar has concentrations roughly two orders of magnitude greater than Earth's and that "this is hard to explain unless it (Venus) is heavily degassed with a larger inventory of primordial volatiles." In further support of a degassed Venus Halliday (2013) notes that the similar Earth and Venus budgets of C and N support a degassed Venus while helping to explain the high ^{20}Ne and ^{36}Ar budgets of Venus. One of the largest stumbling blocks in deciding whether the ^{40}Ar modeling inference is correct is a proper measurement of K/U on Venus, which is presently highly unconstrained. For this reason modeling studies generally use Earth values. Namiki and Solomon (1998) use He to confirm the ^{40}Ar estimates, but they require a Venus in-situ mission to make the appropriate Th and U abundance measurements to characterize the geochemistry necessary for He production. One also needs to consider He escape, an under-explored area of re-

[4] 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.

search given that it depends not only on the ability of He to remain charged or neutral, but also whether Venus had a past magnetic field and how present day measurements can distinguish in situ He in the upper atmosphere from solar wind deposition.

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

3 Venus' Early Evolution & Evidence for Water

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

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

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

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

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

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

An outstanding unsolved and understudied problem is what happened in the epoch of Venus' magma ocean (MO) as it cooled, as this may greatly affect the long-term water inventory of the planet. The timescale of the MO crystallization could be of order a few million years (My) as for Earth (e.g., Katyal et al., 2019; Nikolaou et al., 2019) or greater than 100 My (Hamano et al., 2013; Lebrun et al., 2013). The longevity of the MO and associated hot steam and CO_2 atmosphere is vital to understanding the volatile history of Venus. If the MO and steam atmosphere persist too long then much of the primordial water inventory of Venus could have been lost in its very early history from a stronger solar wind (Chassefière, 1997; Lichtenegger et al., 2016). It is possible that the high D/H ratio we see today (Donahue et al., 1982, 1997) is a relic of that time. 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 My using constant phase lag dissipation theory, suggesting that the planet's rotation rate could have been slow early on. This affects the clouds and atmospheric dynamics. 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 $\sim$16 Earth sidereal days) its climate dynamics work to allow liquid water to persist on the surface for insolations up to ~ 2.6 times that of present day Earth.

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 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 (also pointed out in Fischer-Gödde and Kleine (2017)), as opposed to water-rich carbonaceous chondrites that would have been a mere 0-2% of the total chondrite delivery.

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 My 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 D/H ratios (Donahue et al., 1982, 1997) should be more toward the higher end, $\sim$ 16% of a present day Earth's ocean (Donahue et al., 1997).

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

4 Surface History, Impactors and Climate Evolution

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

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

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

However, *h*ow the large basaltic plains were emplaced remains controversial. A number of authors (e.g., Herrick, 1994; Strom et al., 1994; Basilevsky & Head, 1996) postulated a nearly global ($\sim 80\%$) geologically instantaneous (10-100My) thick (>1km) deposition of basaltic material from volcanic type outflows (GIBVO) that would have buried older craters we cannot observe today (akin to the GRE mentioned above). The outflow depth requirements are determined by the size of the largest impact craters that would have to be completely covered. However, as Ivanov and Head (2013) point out it is possible that the cratering record previous to GIBVO could have also been erased in some manner. The GIBVO model was later augmented and became known as the global stratigraphy hypothesis (e.g., Basilevsky & Head, 1996; Basilevsky et al., 1997; Basilevsky & Head, 1998; J. W. Head & Basilevsky, 1998). Yet another hypothesis to explain the Venus surface record was initially put forward by Phillips et al. (1992) and is termed the Equilibrium Resurfacing Model (ERM). In this model the number of craters observed on Venus today is the result of an equilibrium between constant crater formation (via impacts) and the removal of such craters via on-going tectonic or volcanic methods. Strom et al. (1994) did Monte Carlo calculations to demonstrate why the ERM was not feasible, and that the GIBVO was a better fit to their data. More recent Monte Carlo calculations by Bjonnes et al. (2012) show that the ERM is able to fit the observations.

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

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

Ernst et al. (2017) speculate that "On Venus, voluminous LIP volcanism produced high levels of CO_2 that led to run-away greenhouse effect, and high levels of SO_2 that caused acid rain," but with little supporting evidence. Bullock and Grinspoon (2001) present a similar hypothesis that involves outgassing of SO_2 and H_2O that eventually drive the planet, over 100s of My, into a runaway greenhouse state, but do not mention CO_2. If Venus had LIP volcanism then CO_2 as well as SO_2 can be outgassed if trapped in sediments in the crust as is seen on Earth (e.g., J. W. Head III & Coffin, 1997; V. L. Hansen, 2007; Ernst et al., 2017; Ernst & Youbi, 2017). Hence if Venus had an earlier epoch of liquid water habitability then it is logical to assume that CO_2 would have been trapped in the crust of the planet in the same way it is trapped on Earth today.

However, as noted in Macdonald and Wordsworth (2017) when the surface temperature is warmer (T>300K, see their Figure 2) more water vapor is injected into the stratosphere, which stabilizes the lapse rate. Such warm climates (as seen in the Venus models herein) would prevent the largest plumes from injecting SO_2 into the stratosphere, allowing CO_2 warming without offsetting cooling by H_2SO_4 aerosols.

Another well known mechanism to get Venus from a cool clement state to its present day hot and dry state was proposed by Taylor and Grinspoon (2009) who speculated that water loss via upper atmospheric dissociation and then hydrogen escape would have eventually made the planet dry. Then "With the loss of water, the removal mechanism for CO_2 would be eliminated, and carbonate rocks on the surface would presumably eventually be subducted and lost to thermal decomposition, with the CO_2 being irreversibly returned to the atmosphere through outgassing." This model fits in with more recent research by Wordsworth (2016a) who states that the oxygen left over would eventually find its way to oxidize the mantle and change its redox state, allowing for enhanced nitrogen outgassing which is compatible with the nearly 3 bars of N_2 we see in Venus' atmosphere today. However, an alternative hypothesis is proposed by Gillmann et al. (2009), who suggest that the oxidation of the mantle occurred in the first 100 My of Venus' history. They assume the surface was never cool enough to allow liquid water to condense. The water would again be photodissociated and the hydrogen would have been lost to space as described above. The leftover oxygen would have dissolved in the magma ocean.

Genda and Abe (2005) have proposed that the lack of water on Venus and in Venus' protoplanetary impactors in its early history (in contrast to that of Earth and its water rich impactors) would explain differences in most of the noble gas abundances between Venus and Earth because oceanic protoplanets would enhance atmospheric loss, implying that Venus' original noble gas abundant proto-atmosphere survived to present day on Venus, unlike that of Earth. A lack of water being detrimental to subductive plate tectonics (see Section 8). Sakuraba et al. (2019) have also attempted to get the presently observed nitrogen and noble gas abundances via impact degassing and atmospheric erosion (also see work by, Pham et al., 2011), but unlike Genda and Abe (2005) they believe late accretion may have further influenced the atmosphere of Venus.

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

To summarize, a number of mechanisms exist by which early Venus could have condensed liquid water on its surface. The key ingredient is that it must have been cool enough for long enough in its early history. As shown by Yang et al. (2014); Way et al. (2016, 2018), the rotation rate of a planet greatly affects its climate dynamics. Specifically, for very slow rotation a large contiguous water cloud forms at the substellar point, increasing 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 is it 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., Wordsworth, 2016b). Longstanding 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. Other solutions to Mars' FYSP exist (e.g., Ramirez & Craddock, 2018), although there appears to be little consensus in the community. In general 3-D GCMs have trouble consistently sustaining 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.

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

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

In the 1960-70s several authors investigated the possibility that Venus' rotation period was correlated with its synodic period (Goldreich & Peale, 1966; Gold & Soter, 1969, 1979). Goldreich and Peale (1966) states, "the presence of the Earth may have stabilized the sidereal rotation period of Venus at the value of 243.16 days retrograde." An equilibrium between the atmospheric and body tide of Venus was first proposed by Gold and Soter (1969) to explain Venus' non-synchronous rotation period, based on the incorrect belief at that time that Venus always showed the same face at each inferior conjunction with Earth as proposed by Goldreich and Peale (1966).

The first work to analytically look at Venus' rotation rate and the role of atmospheric tides was by Ingersoll and Dobrovolskis (1978) who extended the earlier work of Lord Kelvin Thomson (1882), Chapman and Lindzen (1970) and Munk and MacDonald (1960). They mention that "Venus probably originated with a retrograde rotation in order to have evolved to the current retrograde state." In the 1980s this work was further extended in a series of papers (Dobrovolskis & Ingersoll, 1980; Dobrovolskis, 1980, 1983). It was clear that Venus' rotation rate was probably determined by a balance between the solid body tidal dissipation and the thermal tides of its thick atmosphere with the sun. Core-mantle friction (CMF) can also play an important role in slowing the spin rate of Venus, as first explored by Goldreich and Peale (1970). Goldreich and Peale (1970) were also the first to demonstrate that core-mantle viscous coupling can drive the obliquity to 0° when less than 90° and to 180° if it is greater than 90° over time.

This remained the state of understanding of Venus' rotational history until the early 2000s when the long-term evolution of its spin state of Venus was investigated in a series of papers by Correia and Laskar (2001); Correia et al. (2003); Correia and Laskar (2003), who suggested that Venus may have rotated faster in the past, and possibly prograde. It also became clear that at faster spin rates CMF plays an important role in slowing the rotation of the planet, but less so at slower spin rates.

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

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

R. Barnes (2017) used an equilibrium tide model with a constant phase lag (CPL) to find that Earth could have ended up tidally locked today (after 4.5Gyr) had it started with a rotation rate of 3 Earth Days or longer (the latter more likely if Earth had no satellite). We have applied the same Equilibrium Tide Model (EqTide)[5] from R. Barnes (2017) to Venus to explore how long it would take Venus to reach a tidally locked state only from solid body tides. As shown in Figure 1 using CPL theory we find that Venus could have been tidally locked within 684Myr if it started with a prograde rotation period of 3 Earth days and zero obliquity. Unfortunately the EqTide model we utilize does not support retrograde spin states, but we expect the differences to be minor. We will continue to explore these issues in a future work using the simulator vplanet (R. Barnes et al., 2019) once this functionality is added. Figure 1 gives further examples for CPL and Constant Time Lag (CTL) theory results using EqTide. For input parameters we assume that the tidal dissipation factor Q=12 and Love number of degree 2 k_2=0.3. These are the same numbers used for the modern Earth in R. Barnes (2017). Recent work by Henning and Hurford (2014) demonstrates that our choice for Q may not be unreasonable for Venus. Henning and Hurford (2014) give estimates of Q for Earth-like planets (see their Fig 15, top-center-row plot) with orbital periods from 0 to 200 days. Venus' 224 d period is slightly outside the range they explore (but can be anticipated from the trend visible in their figure). Our assumption of Q=12 is not far off the Henning and Hurford (2014) 'Warm Earth 2' estimate in their Fig 15. As an aside, Q and k_2 are poorly constrained for present-day Venus. We have even fewer constraints on these values for an ancient Venus, but perhaps those values would be more Earth-like than present day Venus. For example, present day Venus' time lag may not be the same as Earth's because of higher internal temperatures (MacDonald, 1962; Henning & Hurford, 2014). Historically Goldreich and Soter (1966) estimated that Q<17 for Venus, Lago and Cazenave (1979) had values up to Q$\sim$40 while Leconte (2018) estimate Q$\sim$100.

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

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

It is likely that Venus was initially a prograde spinning body (like the other 3 terrestrial planets in our solar system). From that starting point we find the following per-

[5] https://github.com/RoryBarnes/EqTide

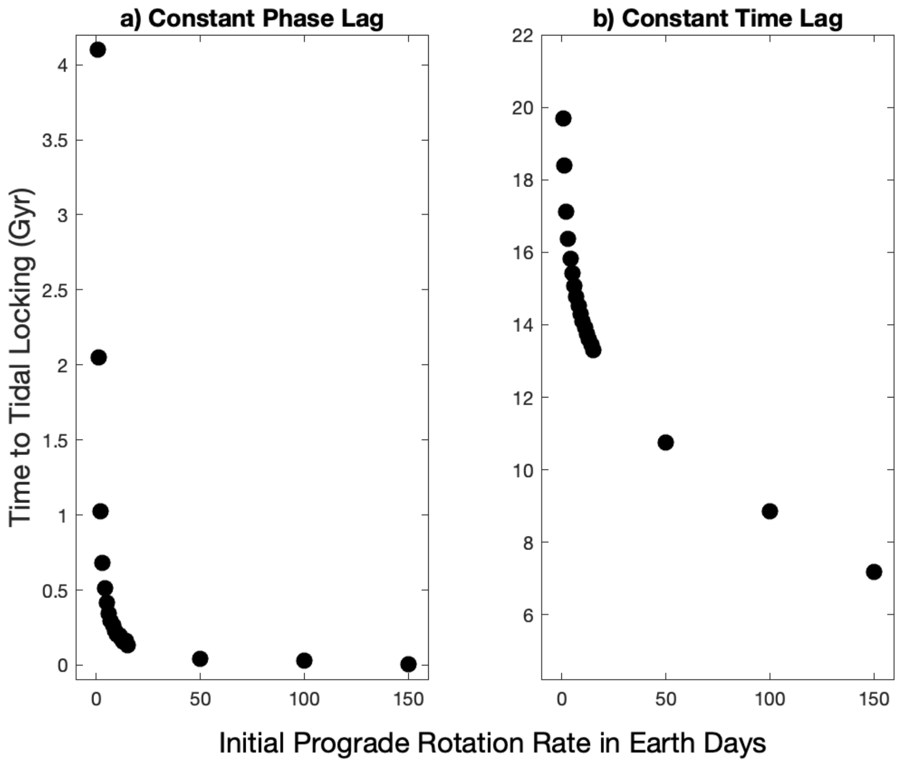

Figure 1. Venus tidal locking timescales using equilibrium tide constant phase (a) and time (b) lag theory. Note that the y-axes have different limits.

haps the most compelling answer to Venus' present day spin state. As shown above there are models that can drive the planet toward a tidally locked state rather quickly. Once spinning more slowly, but still prograde, core-mantle friction could cause its spin axis to orient 180°. Atmospheric tides would prevent the planet from being tidally locked and that is the state the planet has been in since that time as shown in some of the work of Correia and Laskar (2001).

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

Unfortunately, there is little hope that we will ever truly know the rotation rate of Venus through time without a way to either measure its "Geological Orrery" as on Earth (Olsen et al., 2019) and tie that to dynamical models, or find evidence that an impactor played a role in its rotational and hence geochemical evolution as seen in investigations on Earth related to late accretion and its effect on different isotope abundances (e.g., Varas-Reus et al., 2019). In fact Brasser et al. (2016) and S. J. Mojzsis et al. (2019) prefer the hypothesis that the Earth's Late Veneer was mainly delivered by a single Pluto- or Ceres-sized impactor. Hence if a larger object was involved in the late evolution of

Venus' spin or obliquity it may be possible to detect its geochemical fingerprints in a future in-situ mission.

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

6 Methods

All our simulations use ROCKE-3D (Way et al., 2017) a three-dimensional (3-D) General Circulation Model (GCM) developed at the NASA Goddard Institute for Space Studies (GISS). Most simulations use modern Venus' current orbital parameters, slow retrograde rotation period (-243 Earth sidereal days in length) and orbital period (224 sidereal days). In Paper I (plotted herein with ID = B) we looked at a faster rotation period (16 x modern Earth's sidereal day length) to see how the planet's early climate might have responded, and we also look at 16 & 64 day retrograde rotation periods in Venus' early history in this work. Our focus is on changing insolation, topography, land/sea mask, surface water availability and atmospheric constituents. We motivate our choices below.

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

- Arid Venus: This planet has modern Venus topography, but only contains 20cm of water in the subsurface soil layers, soil consisting of 100% sand, and no surface standing water at the start of the simulation. The atmosphere is initialized with zero water vapor and an isothermal temperature profile at 300K. This initial condition is similar to that of Kodama et al. (2019); Abe et al. (2011) who attempt to limit the amount of water vapor in the atmosphere (a strong greenhouse gas) and subsequently push the inner edge of the habitable zone farther inward. However, Kodama et al. (2019); Abe et al. (2011) use modern Earth's rotation rate for all their experiments.
- 10m-Venus: Uses modern Venus topography and places a 10 meter liquid water-equivalent layer in the lowest lying topographic areas. These are treated by the model as lakes, which have no circulation. The soil is a 50/50 sand/clay mix as used in Yang et al. (2014); Way et al. (2016, 2018).
- 310m-Venus: Similar to 10m-Venus, except with a 310 meter water equivalent layer again spread in the lowest lying regions. This is the same topography used in Way et al. (2016) simulations A,B and D.
- 158m-Aqua: This is a simple aquaplanet configuration that is commonly used in the exoplanet community. It uses a fixed 158 meter deep ocean, which corresponds to the bottom of the fifth layer of the ROCKE-3D ocean model. It is a bit shallower than the mean depth of the 310m-Venus ocean, and therefore comes into equilibrium a bit faster while still having a similar heat capacity, while including horizontal heat transport as well as wind-driven and thermohaline overturning circulations.

- 310m-Earth: Similar to 310m-Venus, but using a modern Earth-like land/sea mask with a 310m deep bathtub dynamic ocean (i.e., every ocean grid cell is of a fixed depth of 310m). We call this an Earth-like land/sea mask since it is not exactly modern Earth, but has some modest changes as shown in Way et al. (2018) Figure 8.

The five planets above are then given four types of atmospheres and four different insolations as described below:

- Simulations 1-5: These have a 10 bar 100% CO_2 atmosphere using a solar spectrum and insolation from 4.2Ga from the work of Claire et al. (2012). CO_2 was probably the dominant gas in Earth's early atmospheric evolution (e.g., Kasting, 1993). We pick atmospheric pressures of 1 bar (see next bullet point) and 10 bar to cover the Kasting (1993) ranges (see their Fig 2). Although our 10 bar results are not in equilibrium and the temperatures attained are beyond the upper limits of our radiation tables, the temperatures reached would still allow for water to condense on the surface as shown in Matsui and Abe (1986); Kasting and Ackerman (1986). They are also not inconsistent with the 1-D results presented in Kasting and Ackerman (1986). At the very least they provide a future guide. The 10 bar simulations use a modern Venus rotation rate and obliquity.
- Simulations 6-10: Similar to Simulations 1-5, but these use a 1 bar 97% CO_2 and 3% N_2 atmosphere at 4.2Ga.
- Simulations 11-15: As in Simulations 6-10 but with a rotation period of –16 sidereal Earth days to place the planet on the edge of the fast rotator regime as described in Yang et al. (2014); Way et al. (2018). This allows us to explore the possibility that the planet was rotating more quickly in its early history than today. The choice of a retrograde rotation rate was chosen to be consistent with the present day retrograde rotation, but unpublished simulations with prograde rotation rates with these values produce very similar temperatures. Note that the work of Correia and Laskar (2001, 2003) indicate that prograde rotation rates of 16 days for Venus put its spin axis (obliquity) in a possibly chaotic regime. However, other work by J. W. Barnes et al. (2016) indicate that low obliquity retrograde rotation rates generally have more stable spin axes. Even if there are spin axis variations on geological timescales, it is not possible for us to model those here given that ROCKE-3D simulations are limited to $<$ 10,000 years in length.
- Simulations 16-20: As in Simulations 6-10 but with a rotation period of –64 sidereal Earth days. This allow us to explore the possibility that the planet was rotating somewhat more quickly in its early history but still in the slowly rotating dynamical regime. Again, prograde rotation rates were also used in unpublished results and have similar global surface temperature values.
- Simulations 21-25: These simulations use an atmospheric composition and pressure very similar to modern Earth, namely an N_2-dominated atmosphere with 400ppmv CO_2 and 1ppmv CH_4 with a 1013mb surface pressure. They also use a solar spectrum and insolation at 2.9Ga from Claire et al. (2012). The rotation rate is the same as modern Venus.
- Simulations 26-30: Similar to Simulations 21-25, but with a lower atmospheric surface pressure of 250mb. This is again in the interest of comparative climatology since the Archean atmospheric pressure proxy work of D. Som S. Catling et al. (2012); S. Som et al. (2016) suggests that Earth may have had a surface pressure similar to 250mb at this time.
- Simulations 31-35: Similar to Simulations 21-25, but now using a solar spectrum and insolation from 0.715Ga from the work of Claire et al. (2012).
- Simulations 36-40: Again, similar to Simulations 21-25, but now using a modern solar spectrum and insolation.

- Simulations 41-45: Similar to Simulations 21-25, but now using a modern solar spectrum, but with insolation set to 1.26 times Venus' present day insolation (2.4 times modern day Earth's insolation) to test the boundaries of the inner edge of the habitable zone as in Way et al. (2018).

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

[a]Topography: 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.
[b]Insolation: 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.

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

7 Results and Discussion

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

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

7.1 4.2Ga

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 CO_2-dominated atmosphere. As one would expect from the studies of Yang et al. (2014); Way et al. (2018) the faster spin rate simulations generally have higher temperatures because of the cloud processes discussed in those papers, but almost all of them reach equilibrium at a habitable global mean surface temperature. However, the clouds also differ to some degree because of water availability. Contrary to the work of Abe et al. (2011); Kodama et al. (2019) the Arid-Venus cases all have higher surface temperatures than their counterparts. This is because those previous works used modern Earth's rotation rate, whereas the cloud processes on these slower rotating worlds better regulate the climate, more so the more water that is available for cloud formation. This analysis is backed up by Figure 3 where we plot the shortwave cloud radiative forcing (SWCRF). The Arid-Venus simulations have the smallest (in magnitude) values, because a drier planet has less reflective clouds with less condensed water. In Figure 4 we show the percentage of high level clouds (PCLDH), the dominant of the three cloud types (high, medium, low) in Table 2. Here the distinction between the Arid-Venus simulations and the others is not consistent across the different rotation periods, suggesting that in some cases middle and/or low level clouds make important contributions to SWCRF.

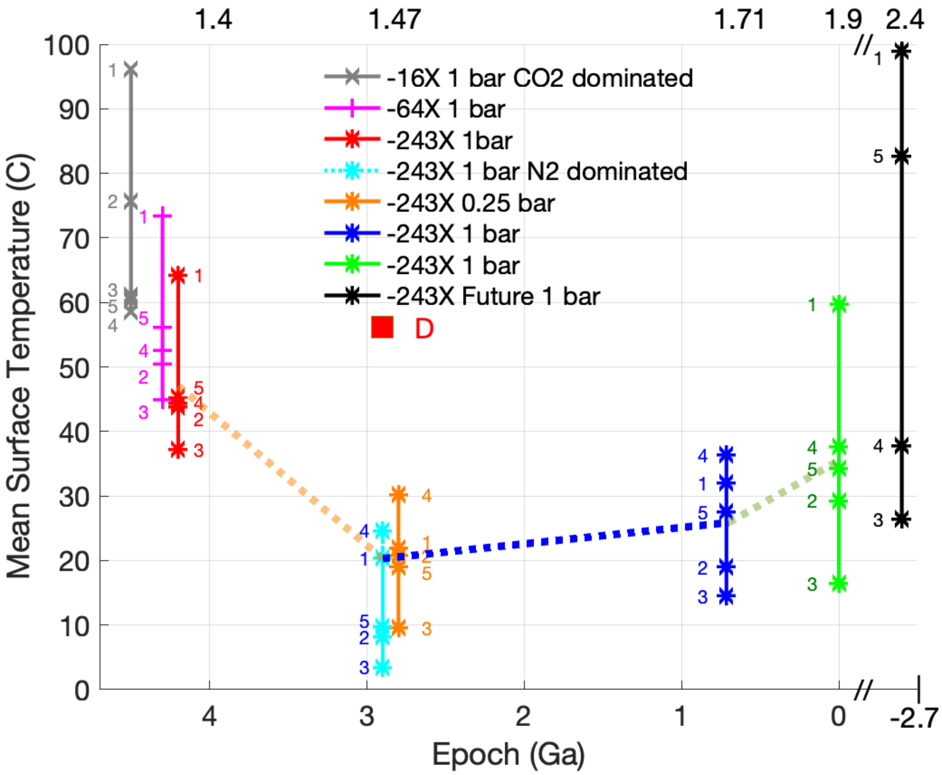

Figure 2. Atmospheric evolutionary scenarios for Venus. Top x-axis is insolation relative to modern Earth ($1.4 = 1.4 \times 1361$ W m^{-2}). Note that the gray, magenta and red data in the left-most section of this plot are all for 4.2 Ga simulations. They are separated purely for visual effect and 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.

7.2 2.9Ga

Here we plot two different sets of simulations for N_2-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 CO_2-dominated atmosphere to a more Earth-like composition via the carbonate-silicate cycle feedback that is believed to regulate CO_2 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 night-

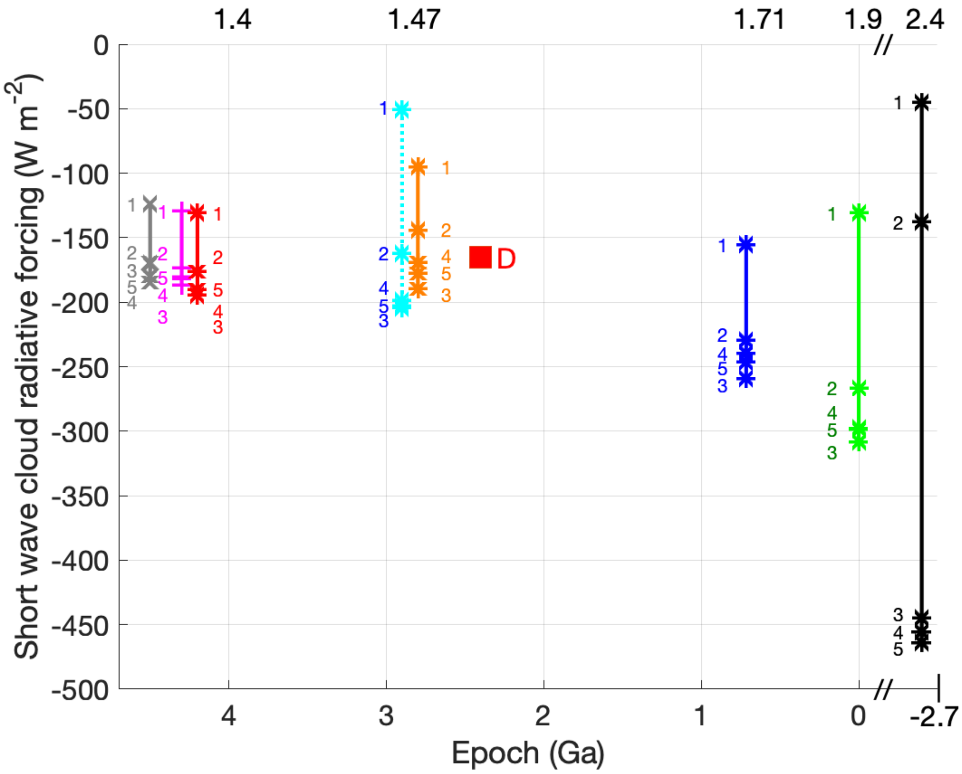

Figure 3. Shortwave cloud radiative forcing for the same evolutionary scenarios, defined as the difference between the solar radiation actually absorbed by the planet and how much would be absorbed if clouds were transparent. This is an estimate of how effective the clouds are at shielding the planet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

time cooling that offsets daytime warming. We also plot Simulation D from Paper I[6] which is an N_2-dominated atmosphere, but is otherwise similar to ID 8 (a CO_2 dominated atmosphere) in Tables 1 and 2. It has a lower mean surface temperature than ID 8 as expected, but is significantly higher than the other simulations with larger rotation periods (ID=21–30) at 2.9Ga. It has less short wave cloud radiative forcing (Figure 3) and lower percentage of high level clouds (Figure 4) compared to the other 310m-Venus simulations at 2.9Ga. This is expected given its faster rotation period, stronger Coriolis force, and less contiguous clouds at the substellar point as discussed in Paper I.

7.3 0.715Ga

This epoch captures a possible final habitable phase on Venus, if the thick CO_2 atmosphere we see today was created by volcanic emissions during the global resurfacing event(s). The spread in surface temperatures between simulations remains about the same as in previous epochs, but for all surface types the temperature is warmer than at 2.9 Ga because of the brighter Sun. Again, the Aqua-158m is has the highest surface temperatures with the Arid-Venus close behind as in the 2.9Ga epoch. The SWCRF is somewhat larger in general, due to both the stronger insolation and slightly reduced high cloud,

[6] The other 3 simulations from Paper I have similar values to their corresponding simulations herein.

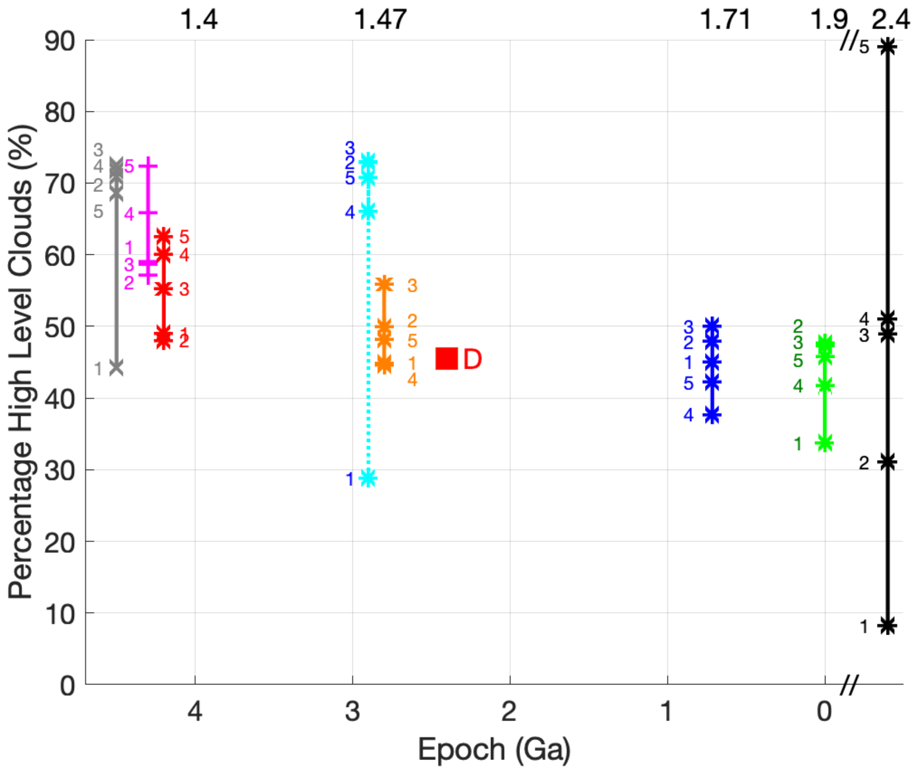

Figure 4. Percentage areal coverage of high level clouds (PCLDH). In Way et al. (2018) it was shown that PCLDH plays a key role in the cloud albedo feedback for slow rotators.

but again the Arid-Venus has the smaller effect. The spread in high level clouds has shrunk considerably from the 1 bar simulations at 2.9Ga.

7.4 Present Day

This suite of simulations at Venus' present day insolation are designed to demonstrate that even under today's Sun the slow rotation cloud feedback effect would have remained strong as Venus' atmospheric pressure and composition remain unchanged. This points to the idea that it was not an increase in insolation that drastically changed Venus' clement climate of earlier epochs, but rather something else, which we speculate to be multiple/simultaneous large igneous provinces. The Arid-Venus simulations again have the highest temperatures and corresponding smallest SWCRF. This is more along lines of what we saw with the simulations at 4.2Ga, with climate forcing by a stronger Sun replacing climate forcing by a thicker greenhouse gas atmosphere as the primary reason for a warm climate.

7.5 Future

Our last set of simulations at insolation values 2.4 times that of present day Earth are meant to show how long a temperate Venus-like world could have remained habitable for a given surface type. Our 10m-Venus simulation is not in equilibrium and so it is not plotted. The Arid-Venus simulation is at nearly 100° Celsius. It appears to be approaching radiative equilibrium, but the simulation crashed after 20 years so it is difficult to be certain. At this point the cloud/albedo feedback for the Arid-Venus case has

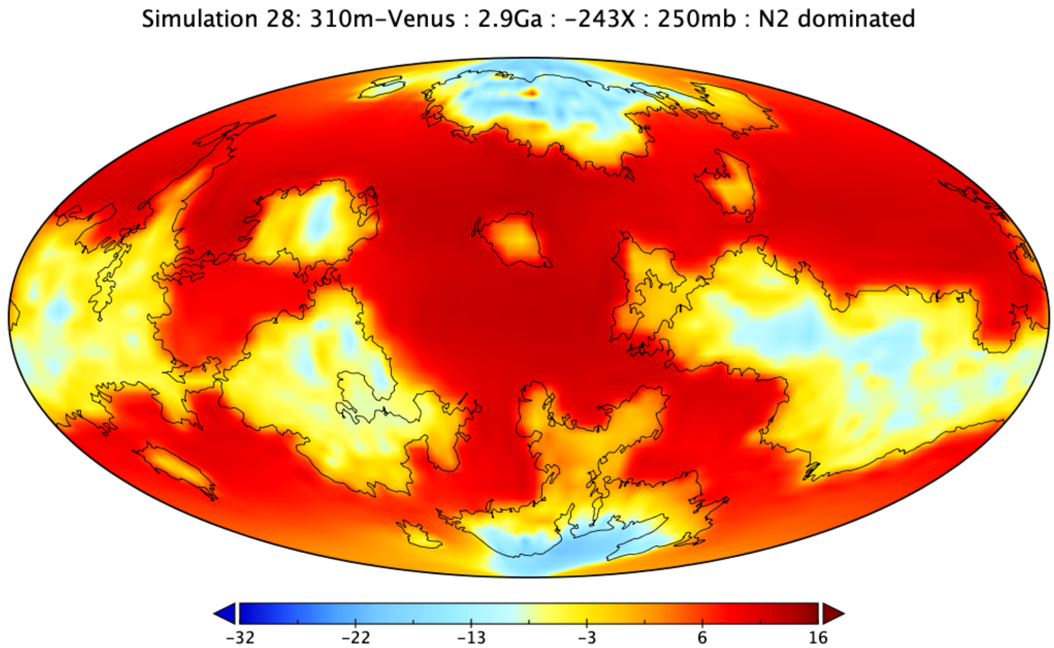

Figure 5. Simulation 28: mean surface temperature over 1/6th of a diurnal cycle.

decreased to Earth-like values (the SWCRF is a mere –50 W m^{-2}). This simulation has the lowest value of PCLDH, which makes it hard to counter the increased insolation at this time in order to keep mean surface temperatures below the boiling point of water.

7.6 General Trends

A few relatively consistent trends are apparent from our simulations. First, the Arid-Venus simulations tend to have the highest surface temperatures, smallest values of SWCRF and lowest percentages of PCLDH. In many cases the 10m-Venus simulations are next, but not always. This may point to the fact that even with 10m of available water the cloud/albedo feedback is generally effective at shielding this slowly rotating world from the intense solar radiation at all epochs when considering what modern Earth receives. The simulations with generally higher water availability and similar percentages of land-to-sea (310m-Venus and 310m-Earth) tend to cluster together in Figures 2,3,4. The 158m-Aqua simulations seem to float in between, perhaps because of the lower surface albedo in combination with the cloud albedo feedback.

Even without a transition to a runaway greenhouse, prior water loss due to the onset of a "moist greenhouse" state may have been important to Venus' evolution. A number of simulations in Table 2 contain stratospheric water concentrations (Q$_{top}$) greater than 3×10^{-3} kg kg^{-1}, the traditional Kasting et al. (1993) limit for onset of the moist greenhouse. However, recent work by Chen et al. (2019) for M-star planets has demonstrated that previous work may have overestimated water loss rates. Hence we should exercise more caution in using 3×10^{-3} kg kg^{-1} as a hard value for the moist greenhouse until similar models are applied to G-star planets. Column Q$_{surf}$ is a check on the amount of water vapor at the surface of the model. ROCKE-3D runs with a fixed molecular mass at model start and ignores the spatially/temporally variable mass of water in calculating pressure gradients, so it is important to keep track of whether water becomes a nonnegligible fraction of atmospheric mass (e.g., 20% of the total or more) as the dynamics in the model will begin to be outside an acceptable range. Only in simulation 45 does this value go over the 20% limit.

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

Figure 7 shows (left panels) the vertically integrated soil moisture and (right panels) lake fraction for two of our Arid-Venus simulations at 2.9 Ga with Earth-like atmospheres: Experiment 21 (1 bar, top panels) and Experiment 26 (250 mb, bottom panels). The Arid-Venus cases are of particular interest because they are initialized with a spatially uniform subsurface soil water reservoir and no standing water bodies, and they then equilibrate to a heterogeneous distribution of surface and subsurface water depending on the climate and circulation and thus the local precipitation-evaporation competition. The 1 bar atmosphere is typical of the behavior of most of the experiments in Table 1: In equilibrium, subsurface water collects primarily in the equatorial region where rising motion and precipitation is prevalent during the daytime, and especially in highland regions such as Aphrodite Terra. Lakes (which are not present in the initial condition) also form preferentially over the equatorial highlands. The 250 mbar simulation is an outlier, with subsurface water and lakes arising primarily at high latitudes. This is reminiscent of what is observed for the methane-ethane lakes on Titan, which Mitchell (2008) is able to reproduce in a GCM when a limited subsurface methane reservoir is assumed.

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

8 Conclusion

Whether Venus' original water survived its initial magma ocean stage, or whether significant water was delivered afterwards, is unknown. It is therefore worth having a theoretical framework that considers the possibility of an early habitable Venus as a starting point for designing future observing strategies that might shed light on Venus' past. In this spirit, we envision the following possible climatic evolution for Venus:

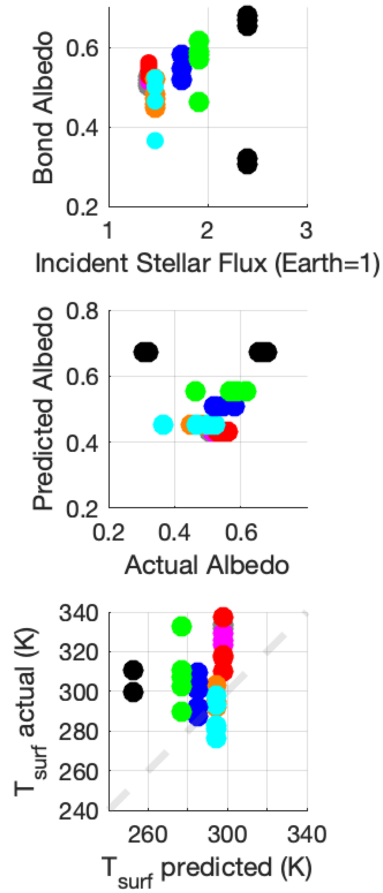

Figure 6. Upper panel: Bond albedo vs. incident solar flux for the planets in Figure 2. Middle panel: Predicted versus actual Bond albedos for the same set of planets after Del Genio et al. (2019). Lower panel: Predicted vs. observed surface temperatures after Del Genio et al. (2019).

1.) Toward the end of the accretion period (∼4.2Ga) 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. 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).

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.

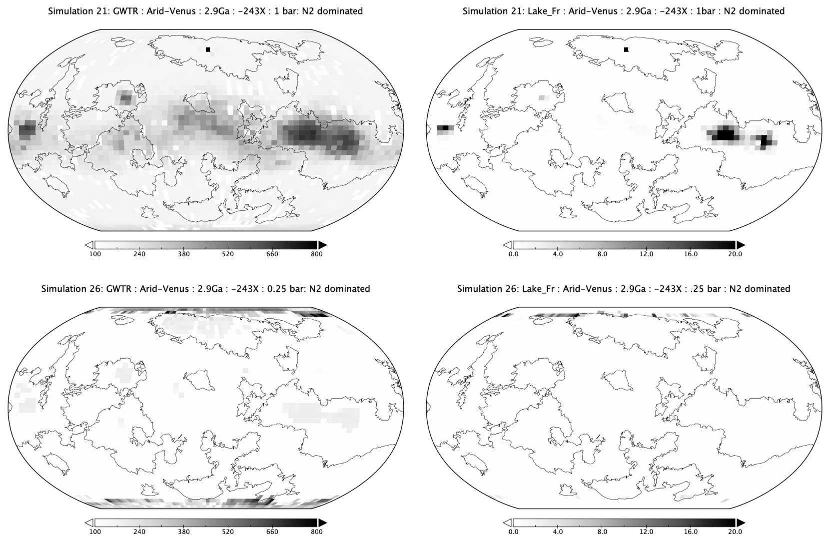

Figure 7. GWTR left panels, LakeFR right panels for Top to Bottom: Simulation 21 and 26 (Arid-Venus).

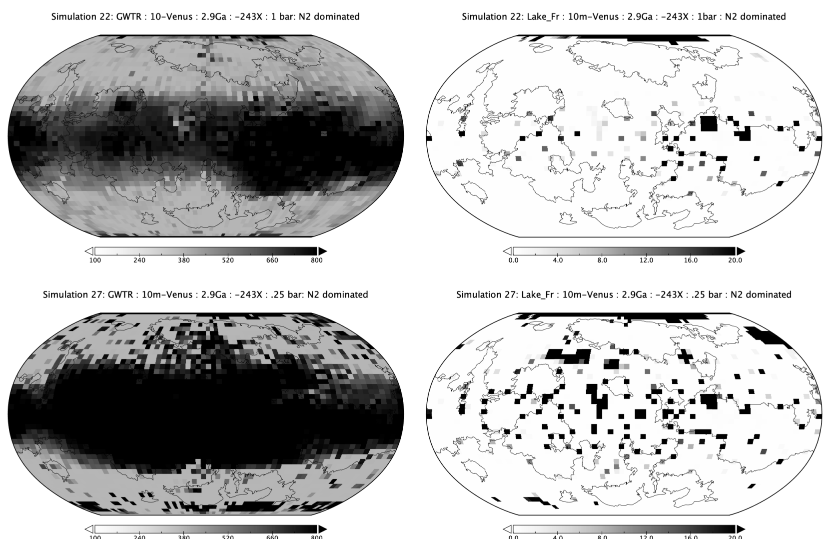

Figure 8. GWTR left panels, LakeFR right panels for Top to Bottom: Simulation 22 and 27 (10m-Venus).

3.) We propose that any stable Venusian climate period came to an end at 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 at the same geological time. It is likely that the ignition of LIPs throughout Earth's history (Ernst, 2014; Ernst et al., 2019) is a random stochastic process. This may imply that multiple large scale LIPs have not occurred simultaneously on Earth by purely random chance, which is fortuitous for life as we know it today. Venus may not have been as fortunate. Unfortunately, little is known about Venus' interior structure today, much less its initial state and subsequent evolution, so the question remains as to whether deterministic evolutionary processes in the interiors of Venus-like planets will inevitably lead to catastrophic changes and uninhabitable end states.

4.) Multiple large scale LIPs would have warmed the world markedly via the release of large amounts of CO_2 via one or more mechanisms and its greenhouse effect on the climate (e.g., Ogden & Sleep, 2012).

5.) This warming could have hastened a movement the onset of a moist (Kasting et al., 1993) and possibly a runaway greenhouse state in which much of the surface water was lost via photodisassociation accompanied by hydrogen escape and an oxidized surface. Recall that present day Venus D/H measurements (if they are accurate) imply .6 to 16% of Earth's present day surficial water stores (Donahue et al., 1997). Hence the timescale of total loss would be at least an order of magnitude faster than that described in Kasting et al. (1993), although there is still uncertainty about the stratospheric conditions under which a moist greenhouse occurs (e.g., Chen et al., 2019) and when a runaway greenhouse is achieved (e.g., Kasting & Ackerman, 1986; Goldblatt et al., 2013; Ramirez et al., 2014).

6.) 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.

7.) 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 over hundreds of millions of years, as described most recently in the work of e.g Rolf et al. (2018); Weller and Kiefer (2019).

Clearly a great deal more modeling work and more observations are required to confirm or refute this hypothesis. Did Venus follow the 'canonical' path with Earth-like conditions throughout most of its history, with its demise and present hothouse state the consequence of a series of LIP events releasing CO_2 bound up in the crust as on Earth, and/or released from the deep interior where CO_2 is more easily sequestered (e.g., Kuramoto & Matsui, 1996)? Or did it become bone dry in an extended magma ocean phase in the first 100Myr, as described in Hamano et al. (2013) for Type II planets?

We will not be able to distinguish between these two scenarios until we return to Venus to make proper noble gas and other elemental and isotopic measurements at the surface (Baines et al., 2013) and better constrain escape processes at the top of the atmosphere through time. The latter will also rely upon how such gases escape from present day Earth given the possibility that Venus may have had a magnetic field in previous epochs, even if it is not clear how important the magnetic field is to escape processes in general (Gunell, Herbert et al., 2018). Likewise, whether the actual evolution of the one Venus we can visit is the ultimate fate of all highly irradiated rocky planets or an accident of an evolutionary path that might have proceeded differently in other circumstances (Lenardic et al., 2016) is not known. The stakes are high for answering this question, since many exoplanets have been discovered in the "Venus zone" just inside the traditional inner edge of the habitable zones of other stars (Kane et al., 2014). Efforts to simultaneously characterize the CO_2 concentrations and climates of a number of these exoplanets, combined with a focused observational strategy for unveiling the history of the "exoplanet next door" to Earth in our own solar system (Kane et al., 2019), will be our best chance to understand whether the envelope for habitability and the emergence of life is much broader than usually assumed.

Table 2. Results

ID[a]	Runtime years	Temp[b] C	Balance[c] W m^{-2}	Q^c_{top} kg/kg	Q^d_{surf} %	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

[a]ID: The colored numbers correspond to those in Figure 2.
[b]Temp: Surface temperature in Celsius.
[b]Balance: These numbers come from 50 year averages unless the Runtime (Column 2) is less than 150 years, then the average is 10 years.
[d]Specific humidity in top layer of the atmosphere.
[e]Surface humidity as percentage of atmosphere.

Appendix A Energy balance and temperature

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.

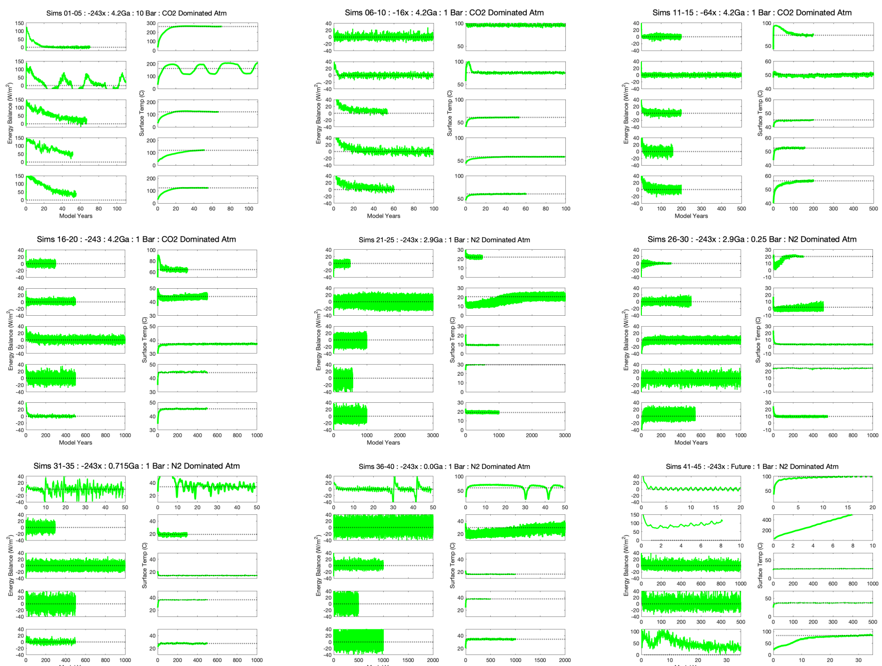

Figure A1. Energy Balance (also called Net Radiative Balance) in the left columns and surface temperature in the right columns as a function of simulation year for all simulations in this study. Note that not all limits on the x or y axes are the same.

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

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Figure 1.

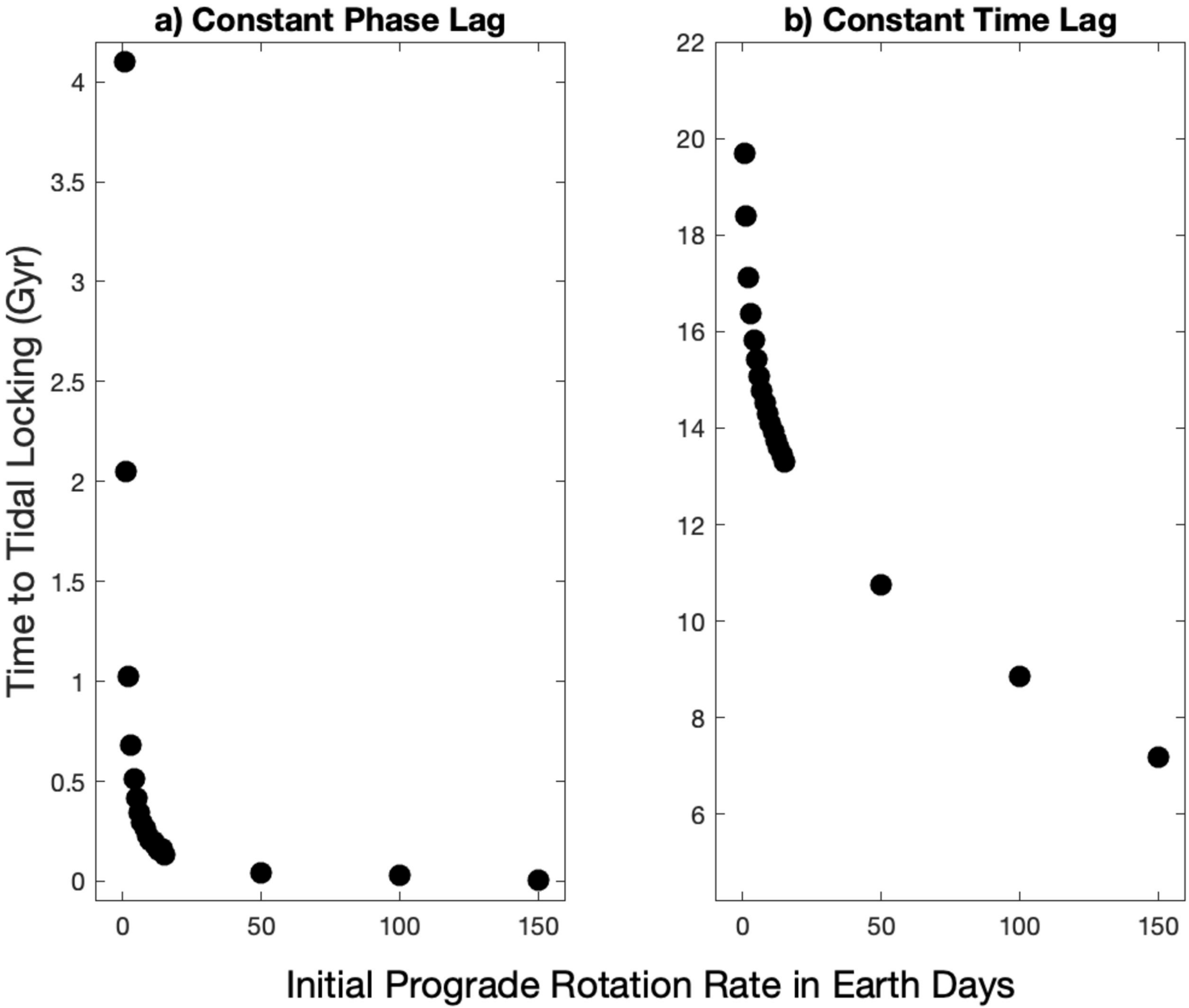

a) Constant Phase Lag
b) Constant Time Lag
Time to Tidal Locking (Gyr)
Initial Prograde Rotation Rate in Earth Days
0
0.5
1
1.5
2
2.5
3
3.5
4
6
8
10
12
14
16
18
20
22
0
50
100
150

Figure 2.

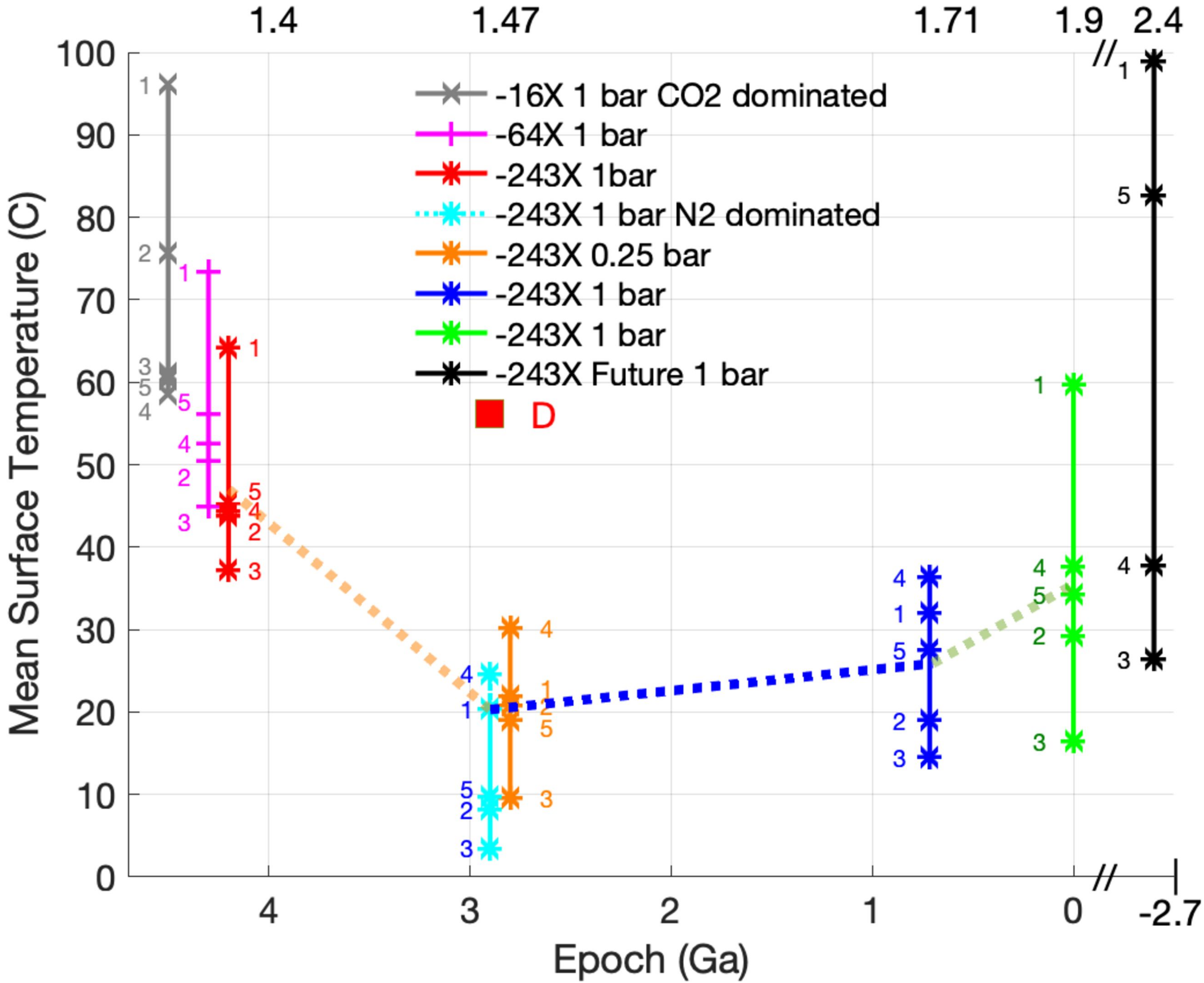
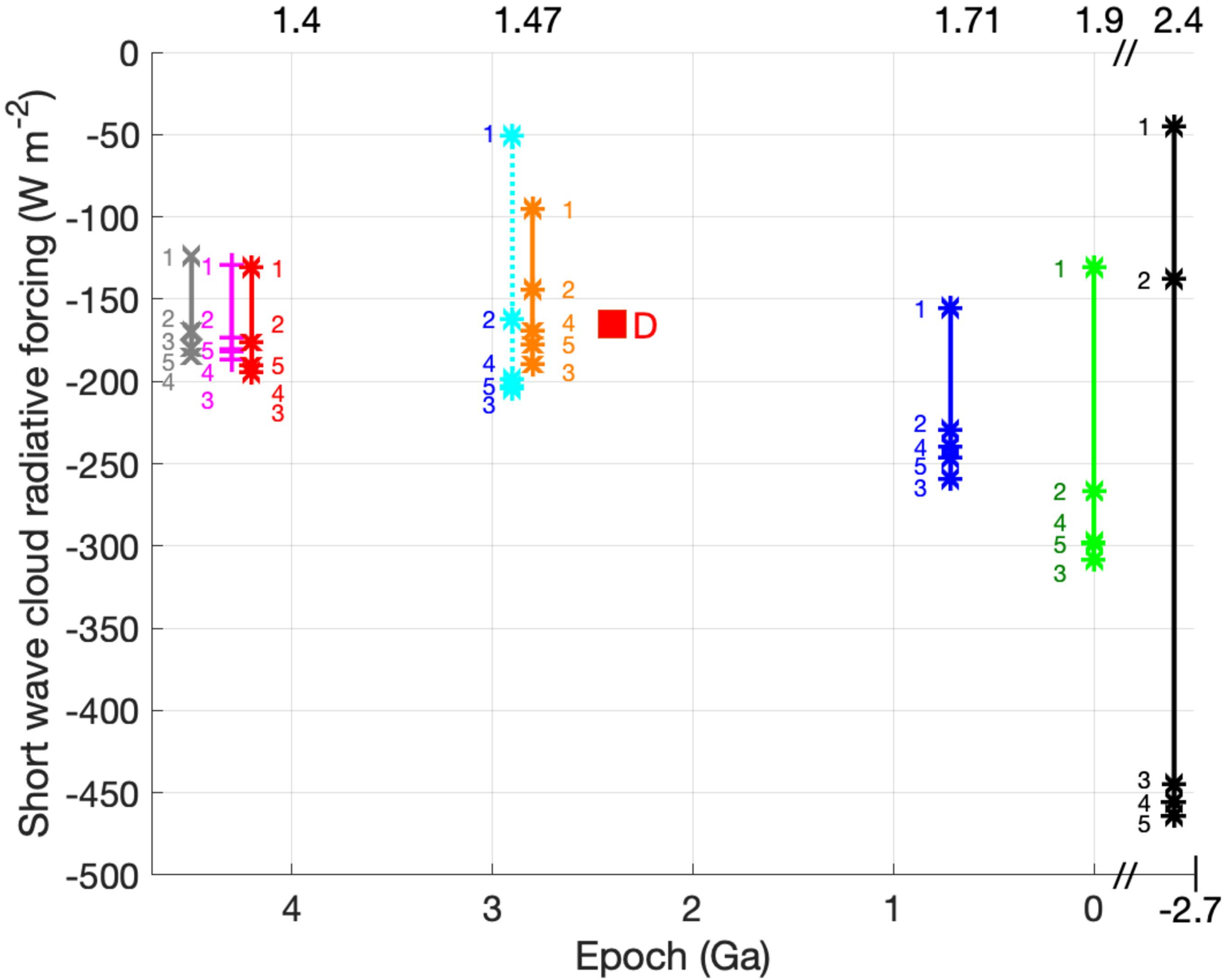
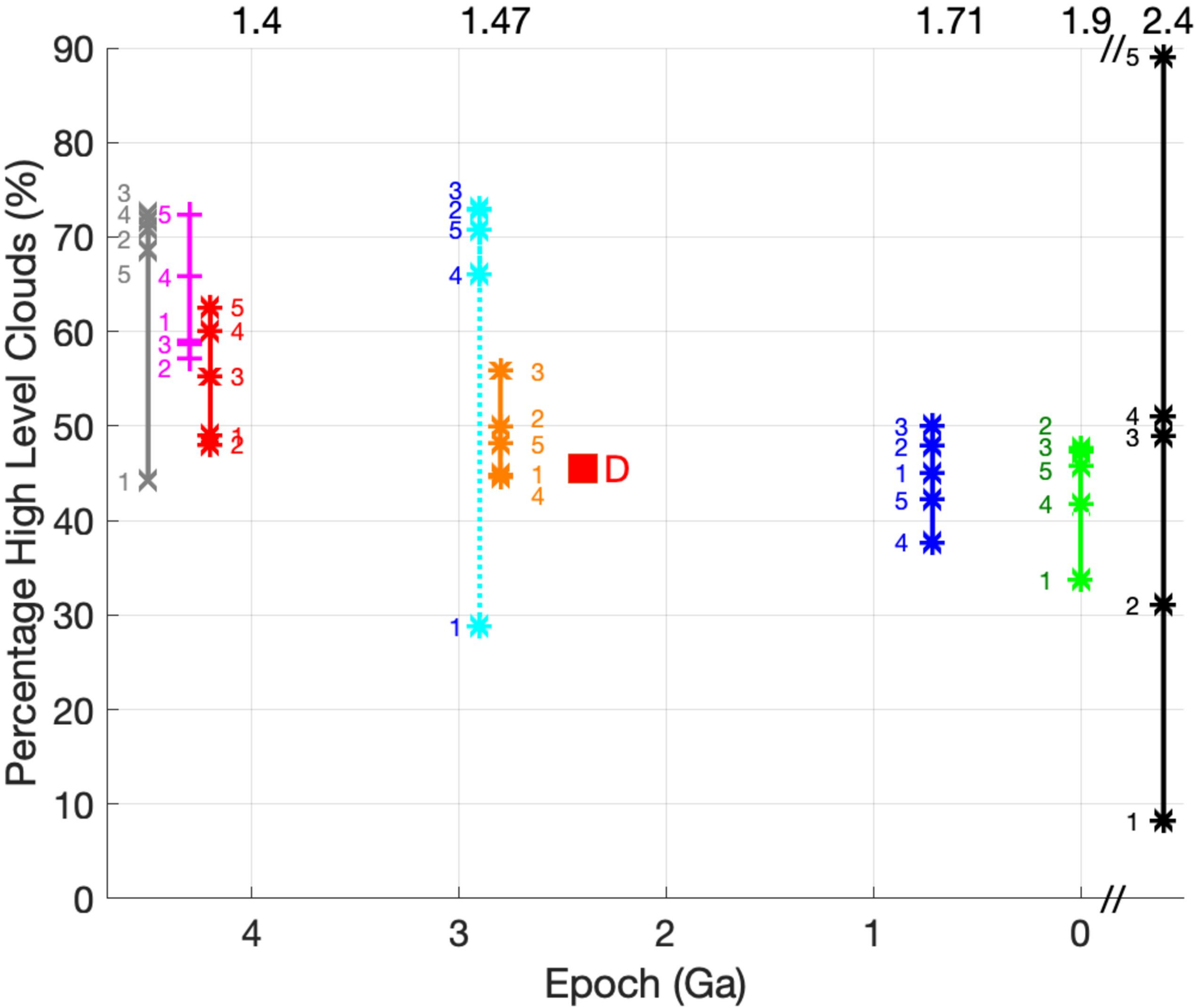

1.4
1.47
1.71
1.9
2.4
-16X 1 bar CO2 dominated
-64X 1 bar
-243X 1bar
-243X 1 bar N2 dominated
-243X 0.25 bar
-243X 1 bar
-243X 1 bar
-243X Future 1 bar
D
Mean Surface Temperature (C)
Epoch (Ga)
-2.7

Figure 3.



1.4
1.47
1.71
1.9
2.4
Short wave cloud radiative forcing (W m^{-2})
Epoch (Ga)
D
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
-500
4
3
2
1
0
-2.7

Figure 4.



1.4
1.47
1.71
1.9
2.4
Percentage High Level Clouds (%)
Epoch (Ga)
D

Figure 5.

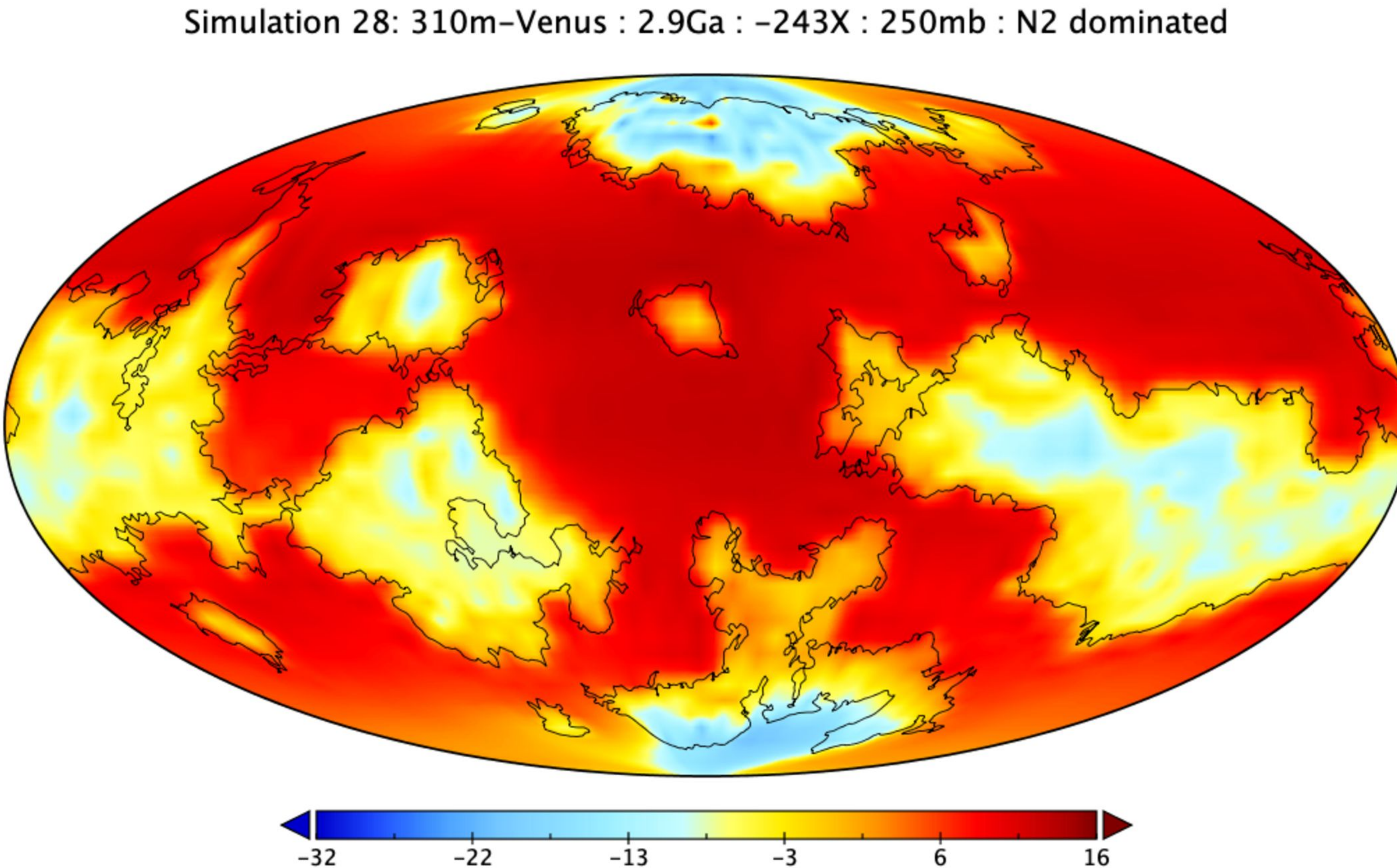
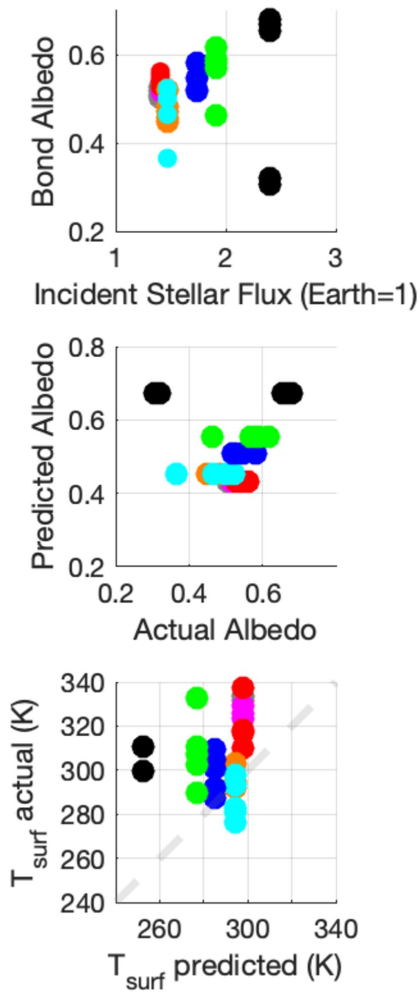

Simulation 28: 310m-Venus : 2.9Ga : -243X : 250mb : N2 dominated
-32
-22
-13
-3
6
16

Figure 6.



Bond Albedo
0.2
0.4
0.6
1
2
3
Incident Stellar Flux (Earth=1)
Predicted Albedo
0.2
0.4
0.6
0.8
Actual Albedo
T_{surf} actual (K)
240
260
280
300
320
340
T_{surf} predicted (K)

Figure 7a.

Simulation 21: GWTR : Arid-Venus : 2.9Ga : -243X : 1 bar: N2 dominated

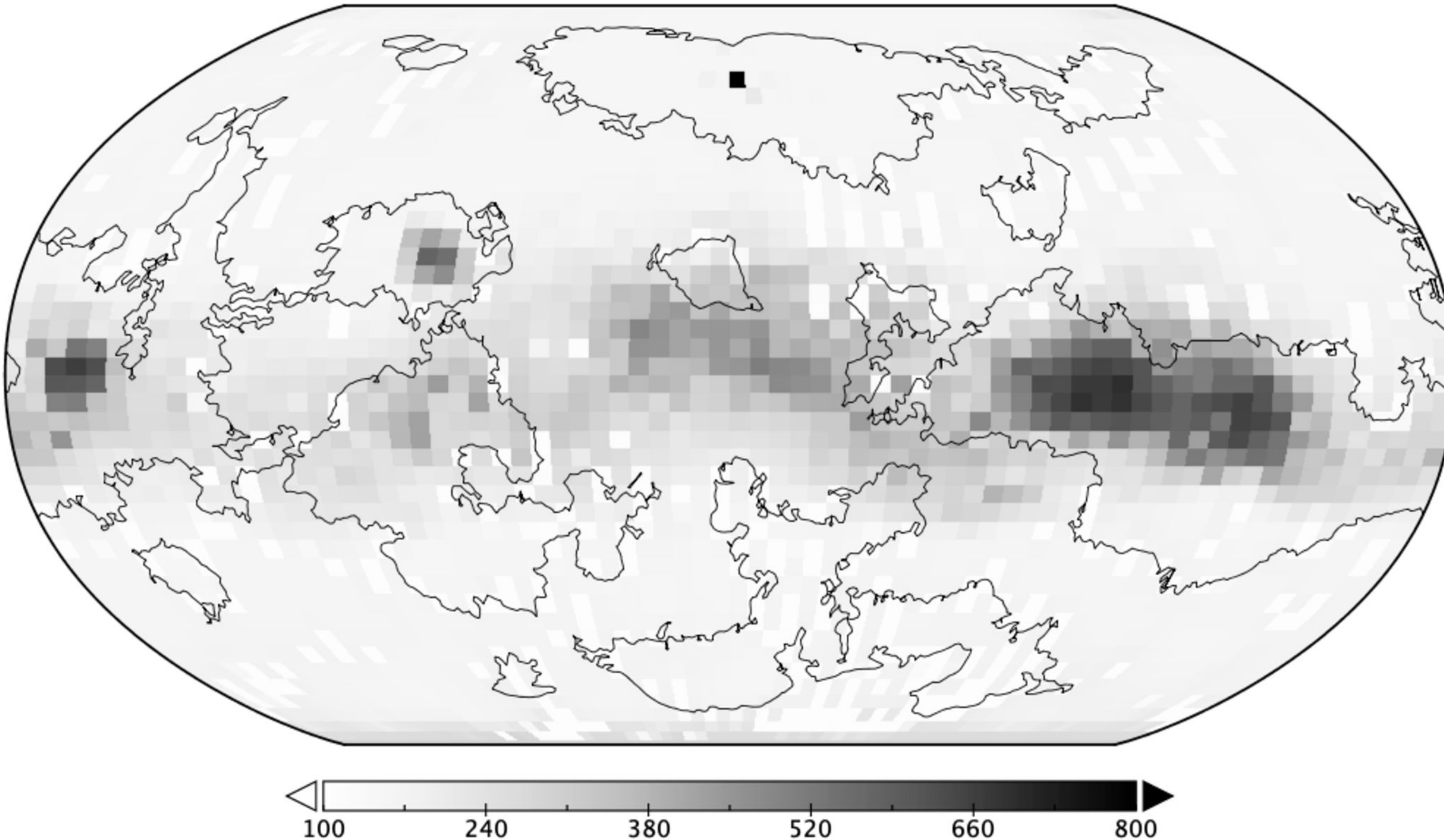


Figure 7b.

Simulation 21: Lake_Fr : Arid-Venus : 2.9Ga : -243X : 1bar : N2 dominated

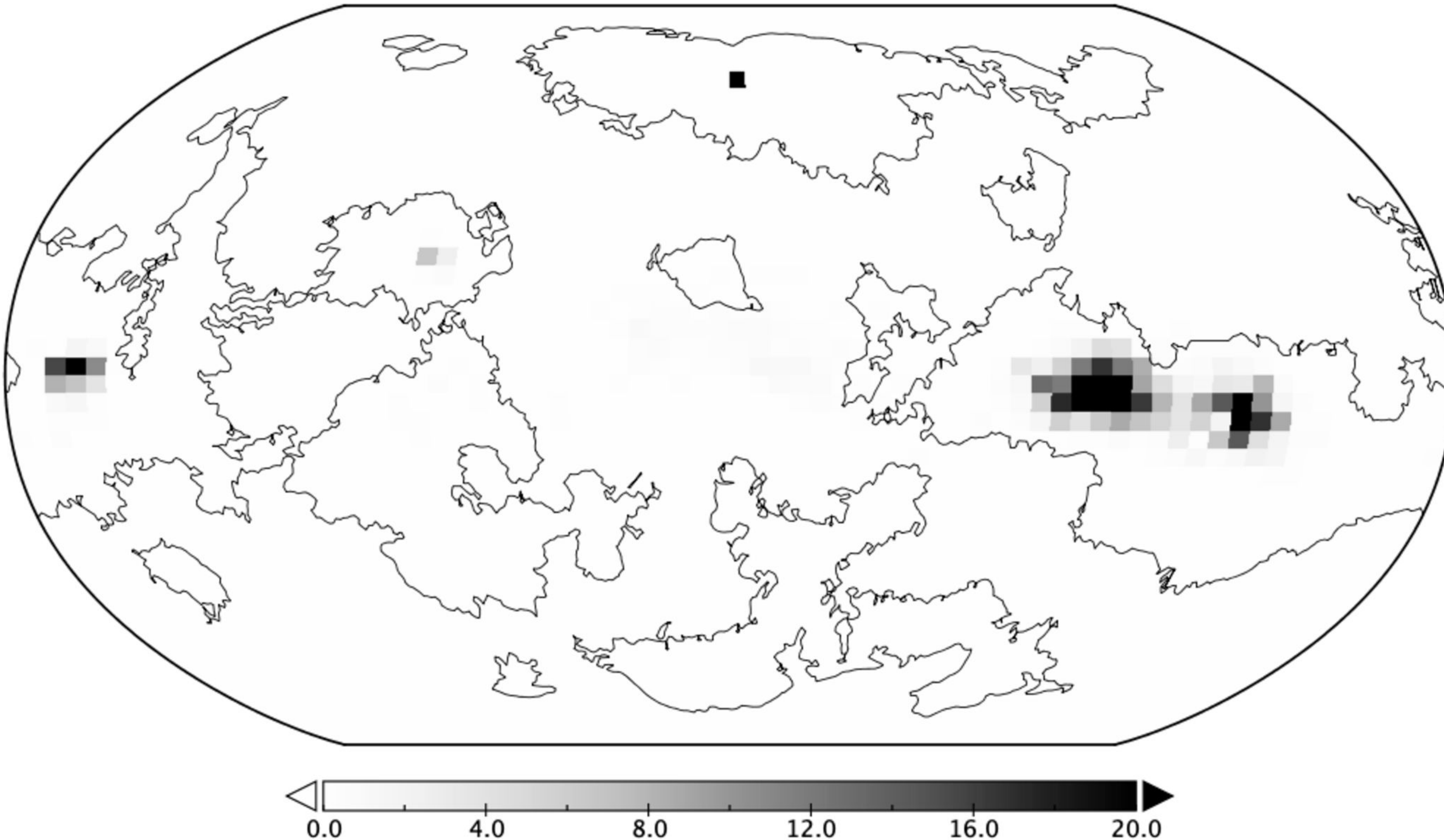


Figure 7c.

Simulation 26: GWTR : Arid-Venus : 2.9Ga : -243X : 0.25 bar: N2 dominated

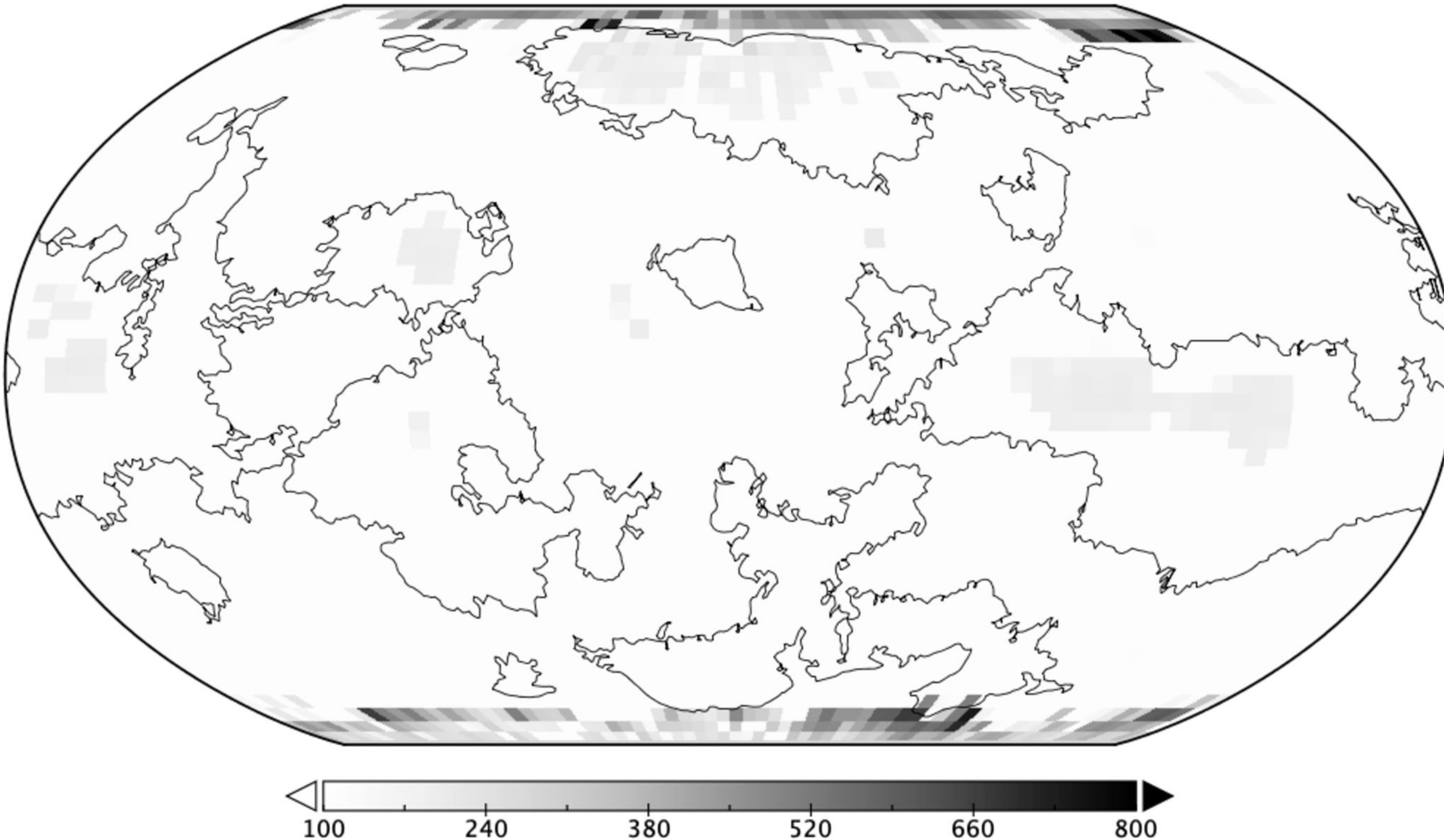


Figure 7d.

Simulation 26: Lake_Fr : Arid-Venus : 2.9Ga : -243X : .25 bar : N2 dominated

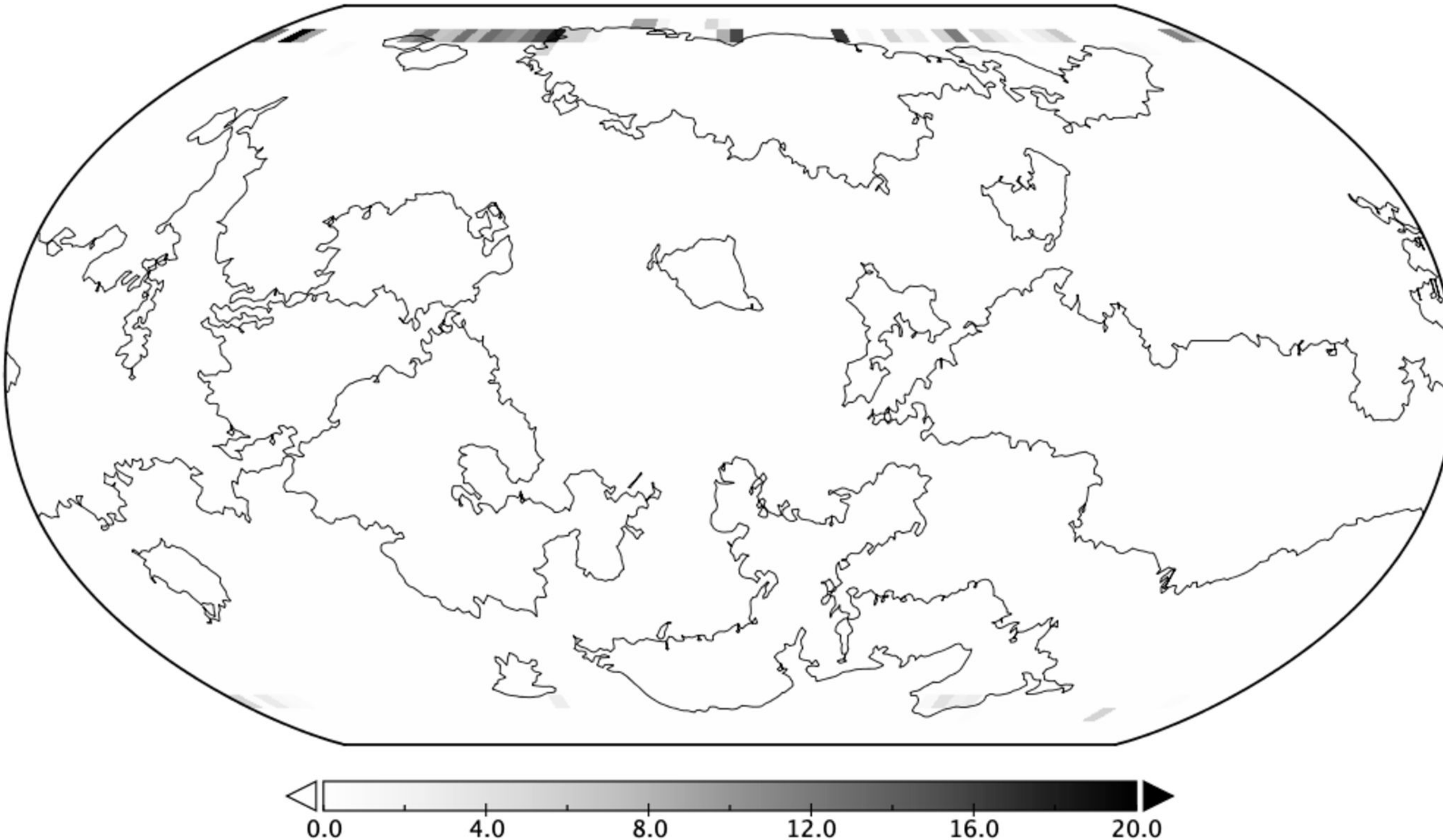


Figure 8a.

Simulation 22: GWTR : 10-Venus : 2.9Ga : -243X : 1 bar: N2 dominated

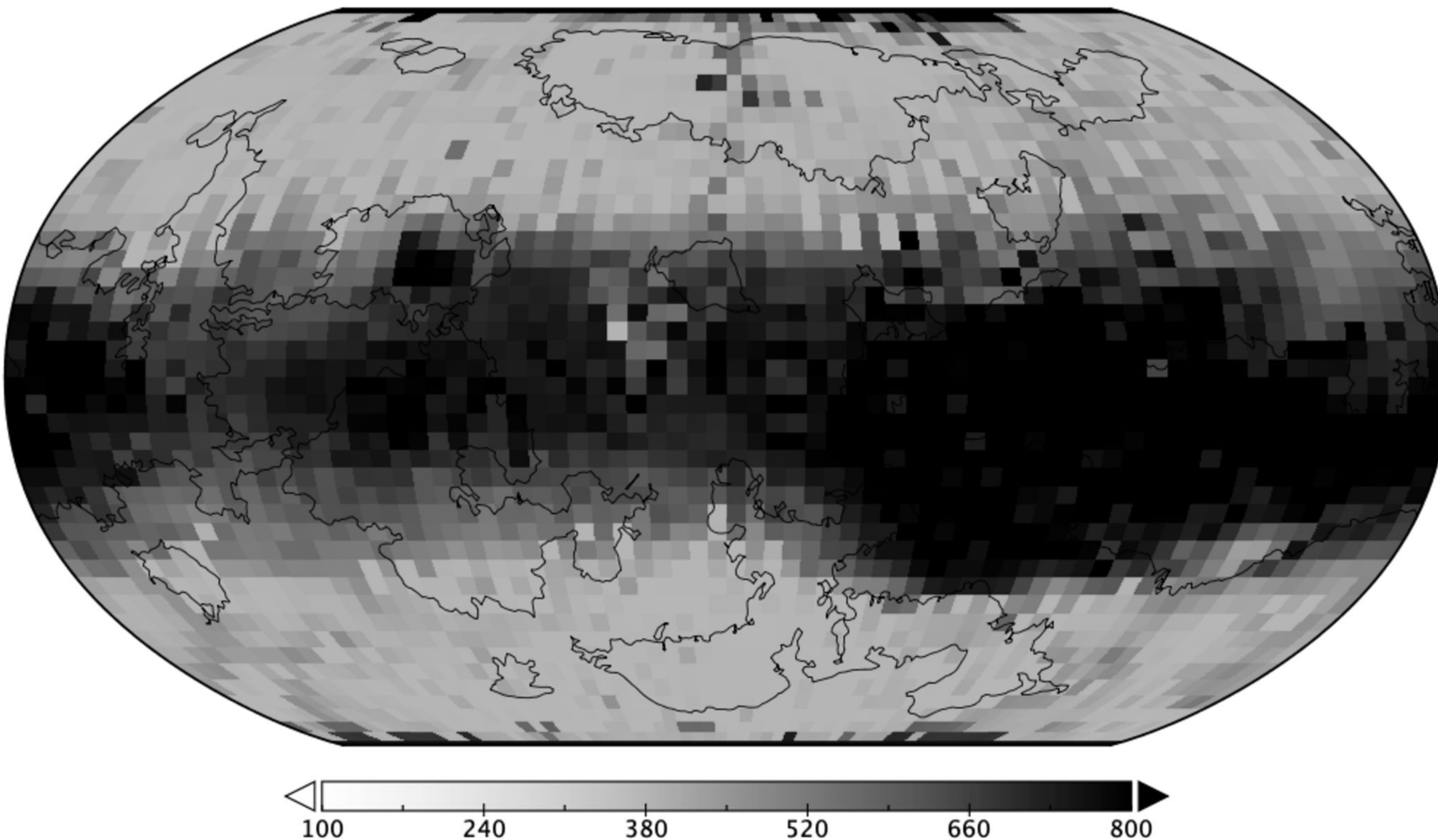


Figure 8b.

Simulation 22: Lake_Fr : 10m-Venus : 2.9Ga : -243X : 1bar : N2 dominated

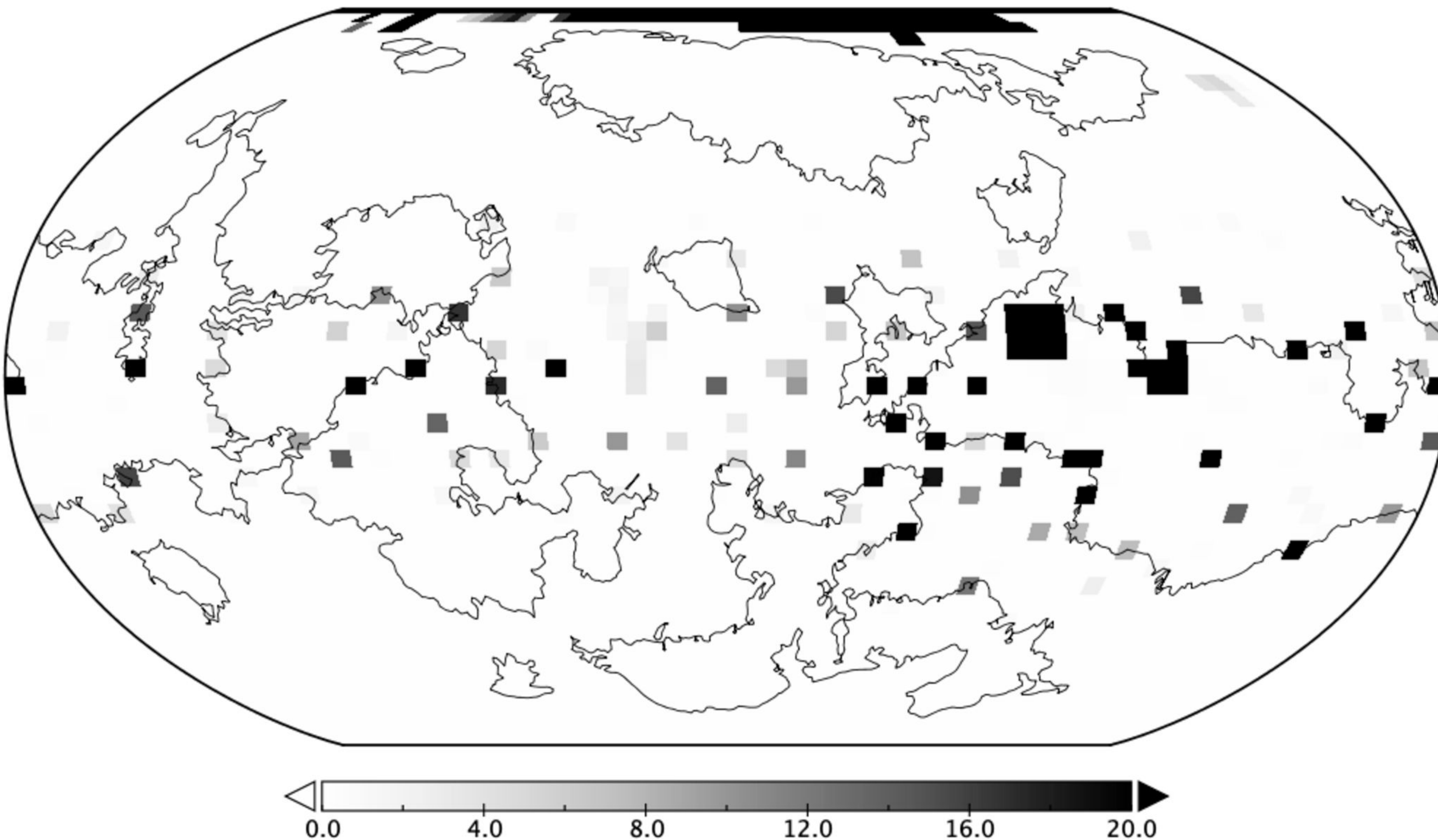


Figure 8c.

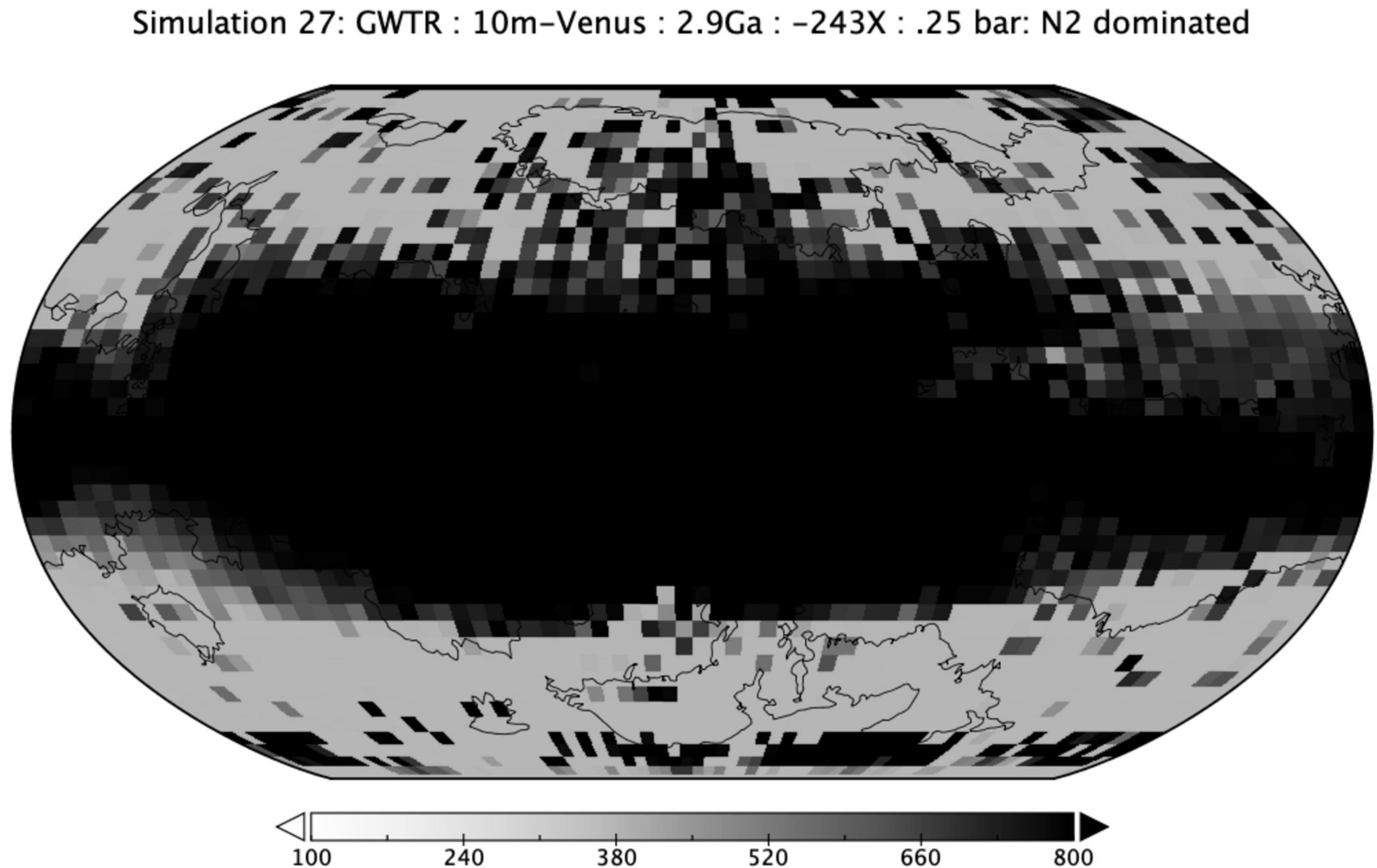

Simulation 27: GWTR : 10m-Venus : 2.9Ga : -243X : .25 bar: N2 dominated
100
240
380
520
660
800

Figure 8d.

Simulation 27: Lake_Fr : 10m-Venus : 2.9Ga : -243X : .25 bar : N2 dominated

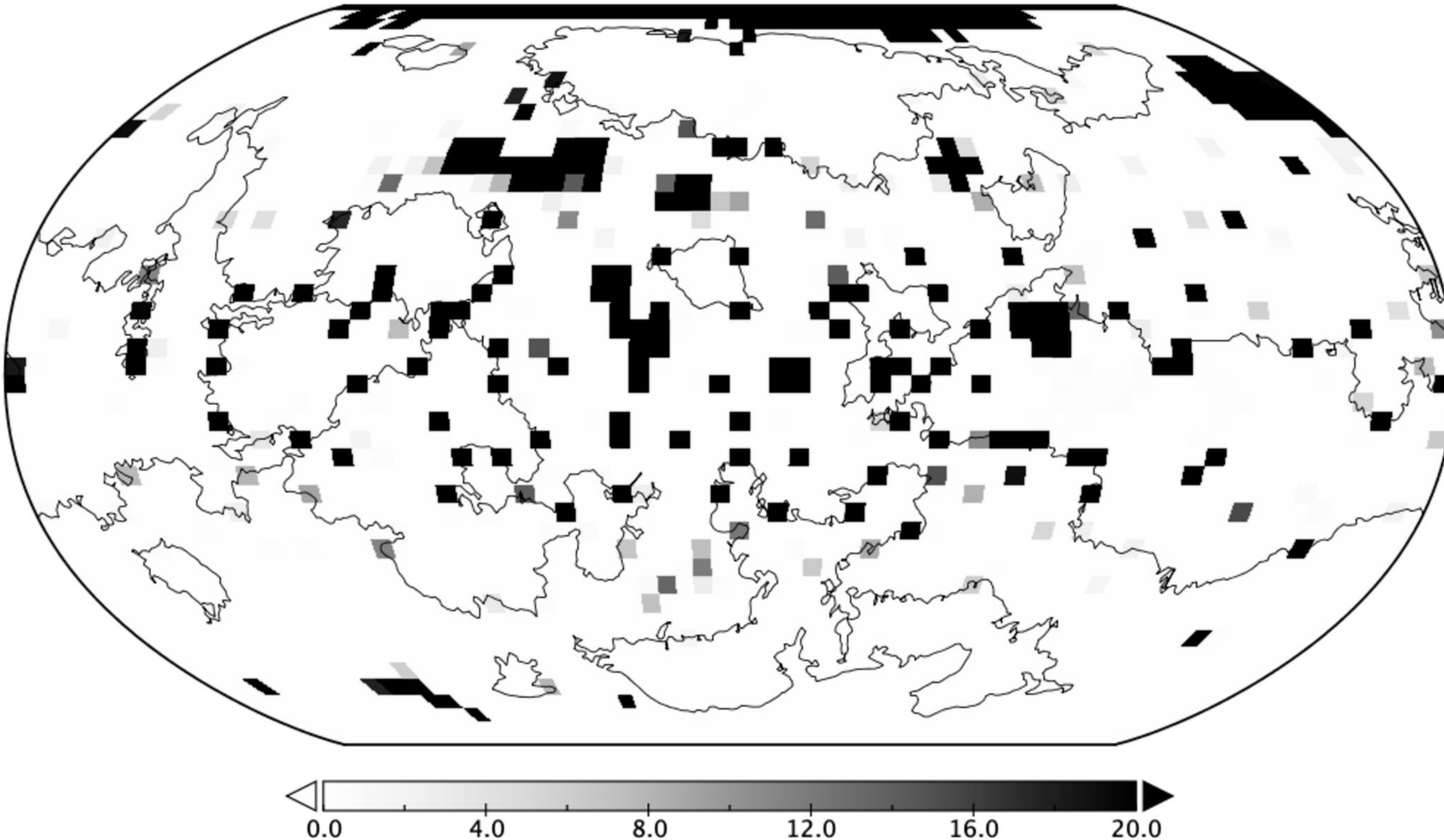
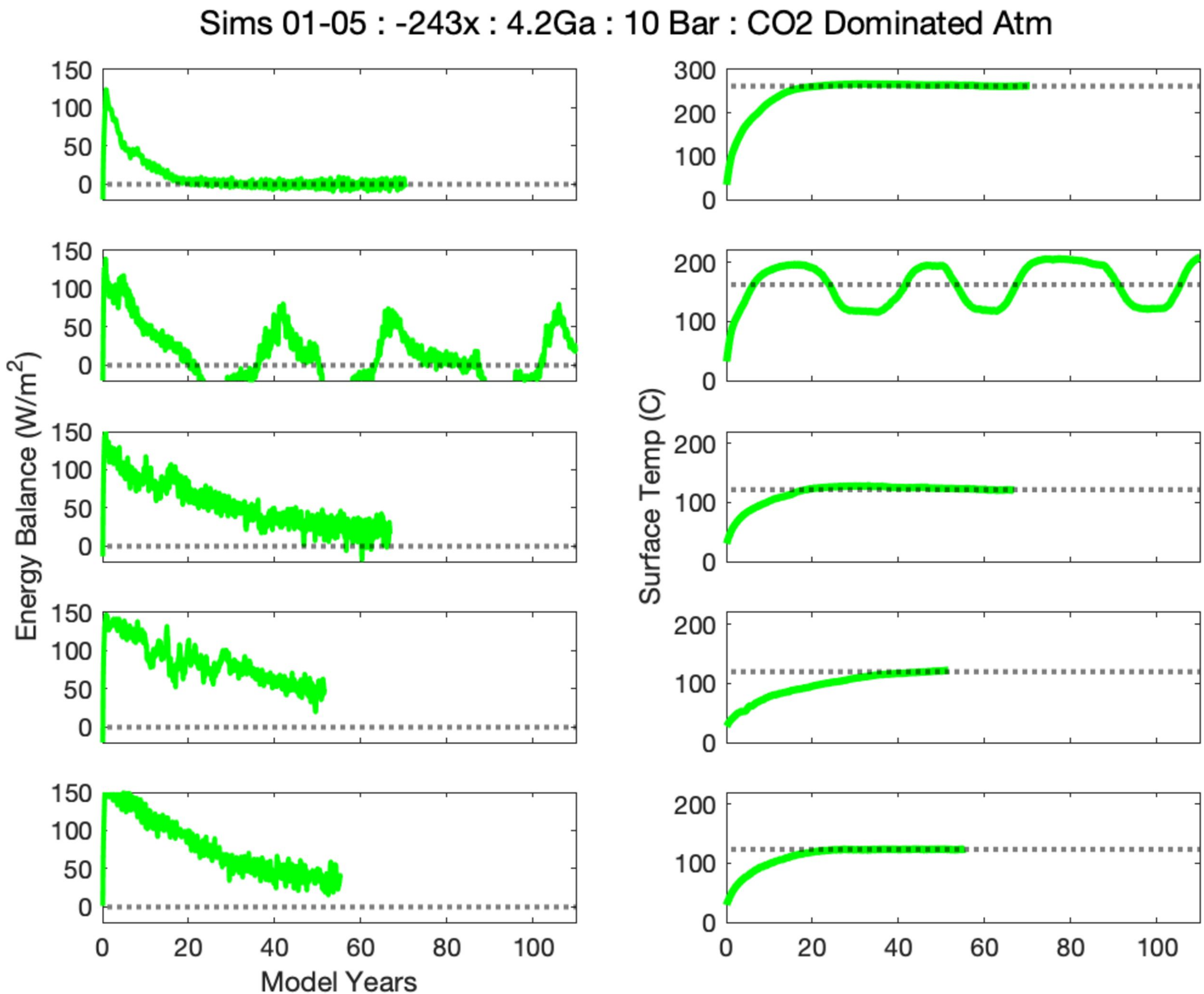


Figure 9a.



Sims 01-05 : -243x : 4.2Ga : 10 Bar : CO2 Dominated Atm
Energy Balance (W/m^2)
Surface Temp (C)
Model Years
0
20
40
60
80
100
150
100
50
0
300
200

Figure 9b.

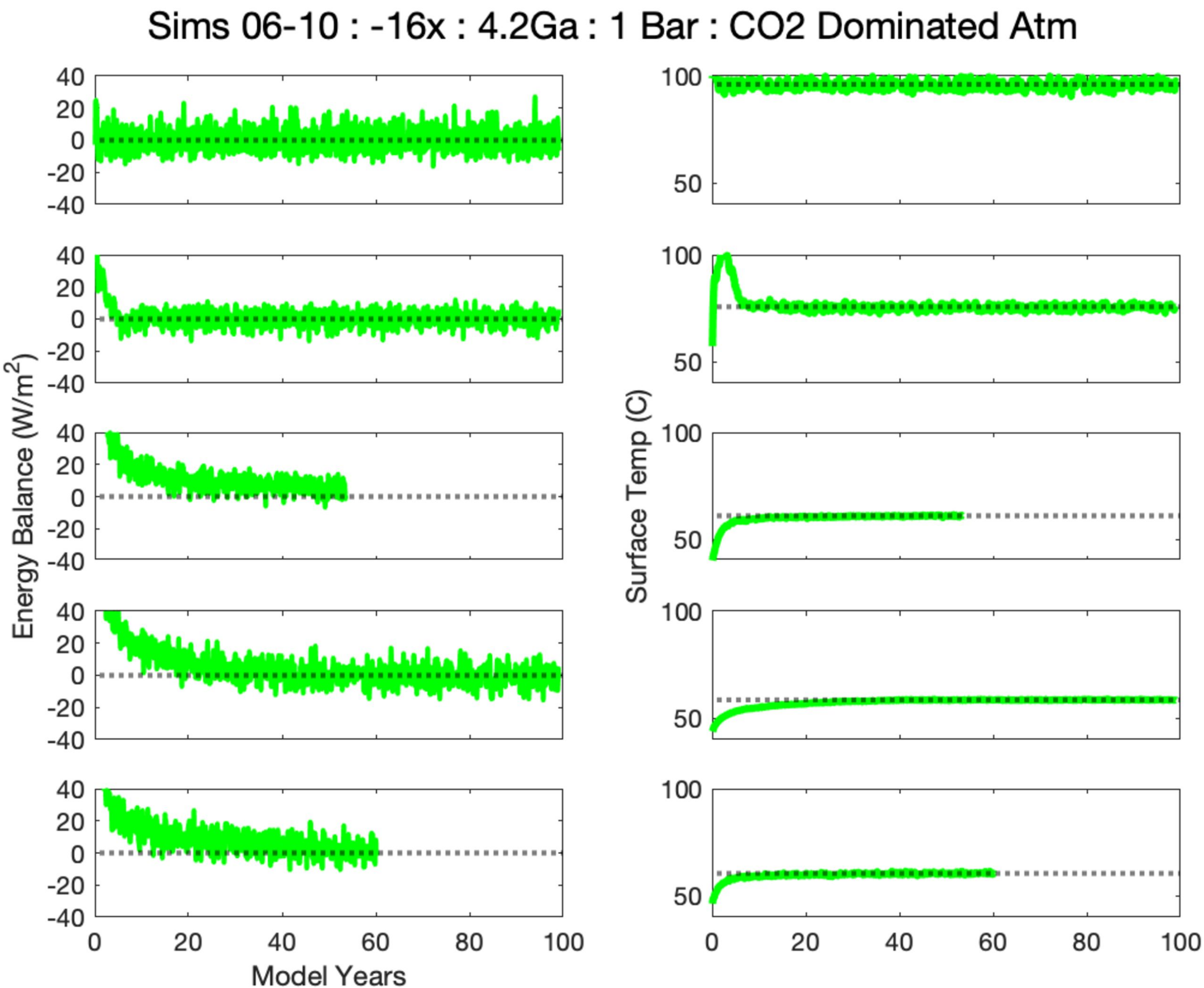
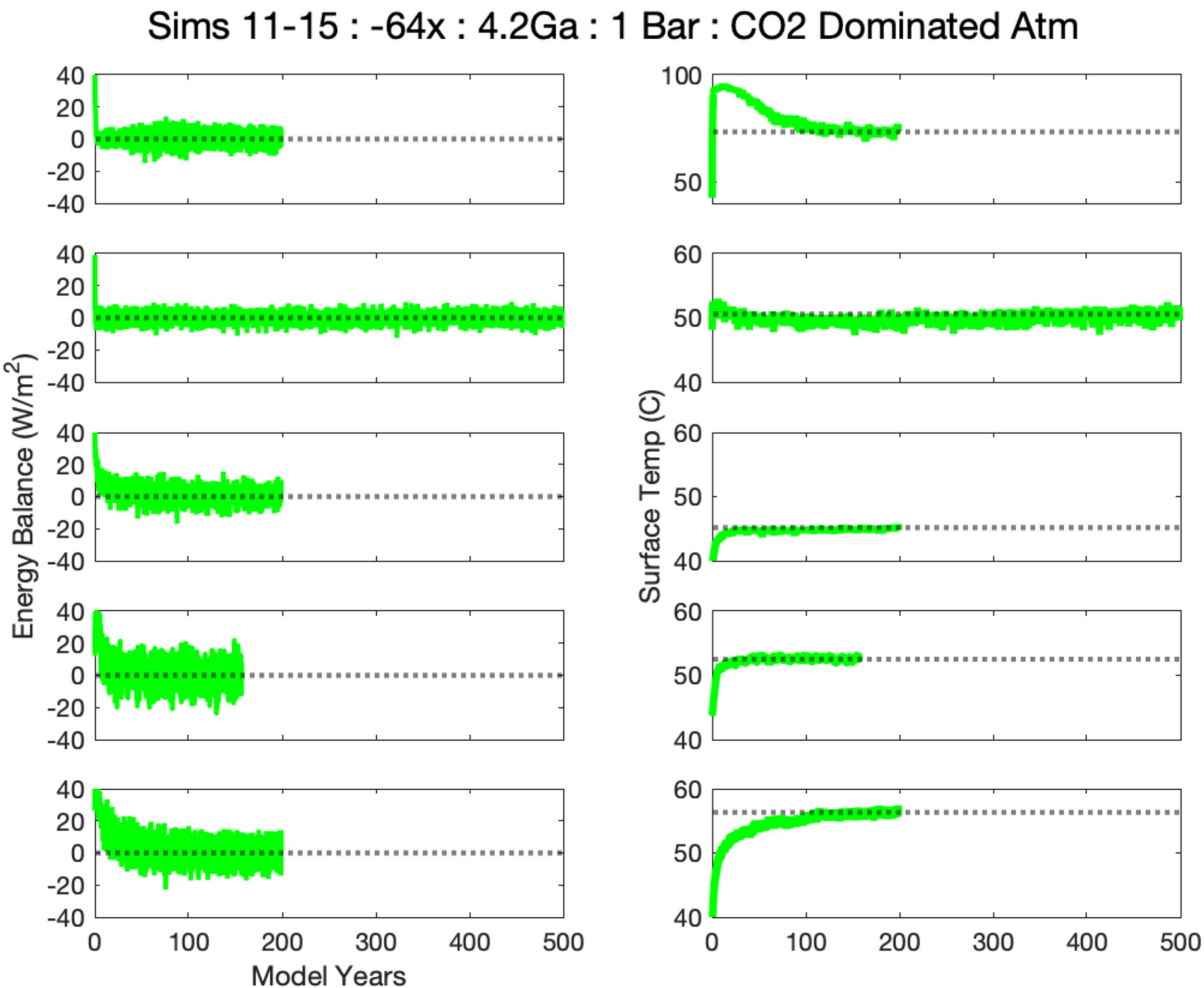
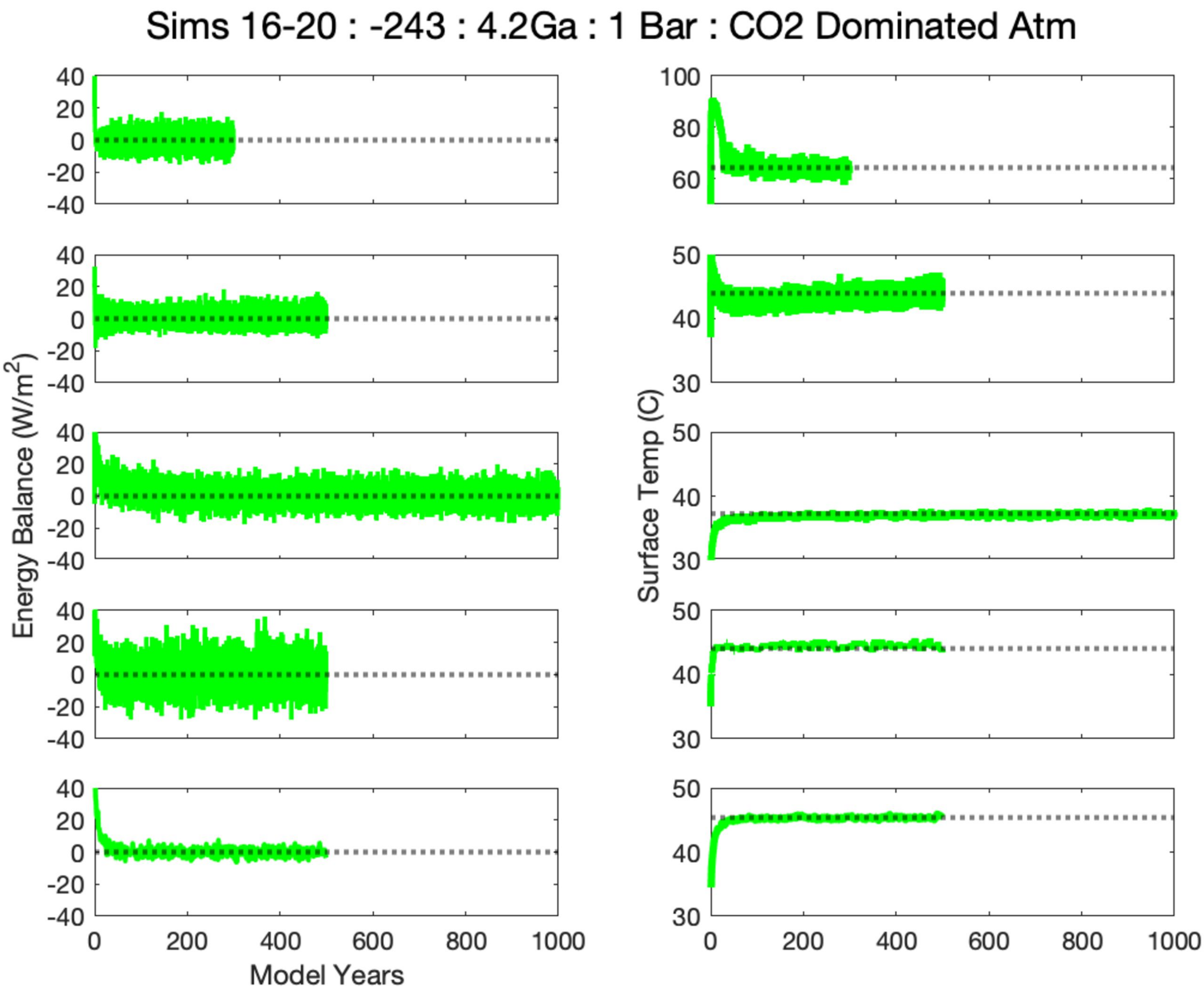

Sims 06-10 : -16x : 4.2Ga : 1 Bar : CO2 Dominated Atm
Energy Balance (W/m^2)
Surface Temp (C)
Model Years
40
20
0
-20
-40
100
50
0
20
40
60
80
100

Figure 9c.



Sims 11-15 : -64x : 4.2Ga : 1 Bar : CO2 Dominated Atm
Energy Balance (W/m2)
Surface Temp (C)
Model Years
40
20
0
-20
-40
100
50
60
0
100
200
300
400
500

Figure 9d.



Sims 16-20 : -243 : 4.2Ga : 1 Bar : CO2 Dominated Atm
Energy Balance (W/m^2)
Surface Temp (C)
Model Years
0
200
400
600
800
1000

Figure 9e.

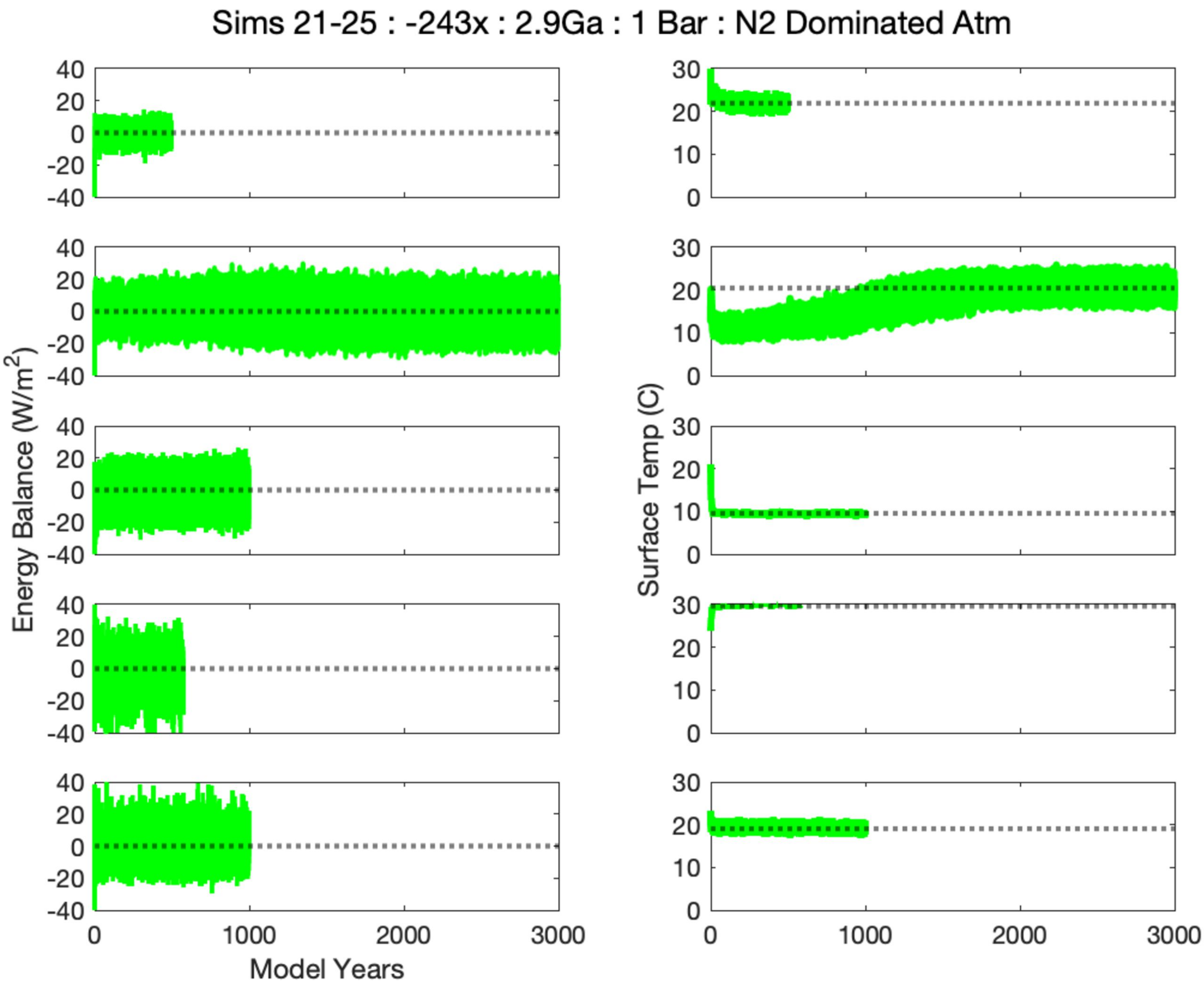

Sims 21-25 : -243x : 2.9Ga : 1 Bar : N2 Dominated Atm
Energy Balance (W/m^2)
Surface Temp (C)
Model Years
0
1000
2000
3000
40
20
0
-20
-40
30
20
10
0

Figure 9f.

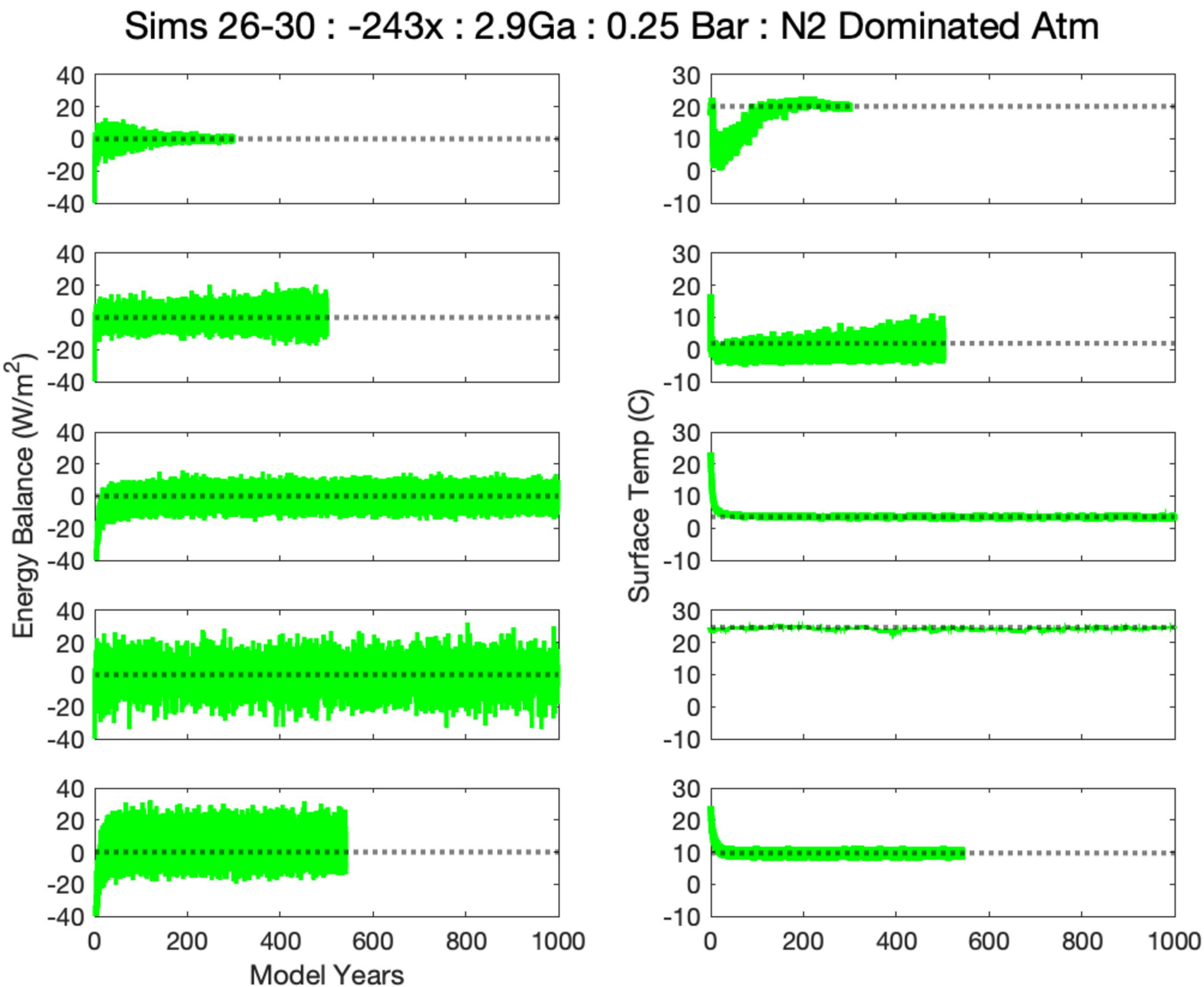

Sims 26-30 : -243x : 2.9Ga : 0.25 Bar : N2 Dominated Atm
Energy Balance (W/m2)
Surface Temp (C)
Model Years
40
20
0
-20
-40
30
20
10
0
-10
0
200
400
600
800
1000

Figure 9g.

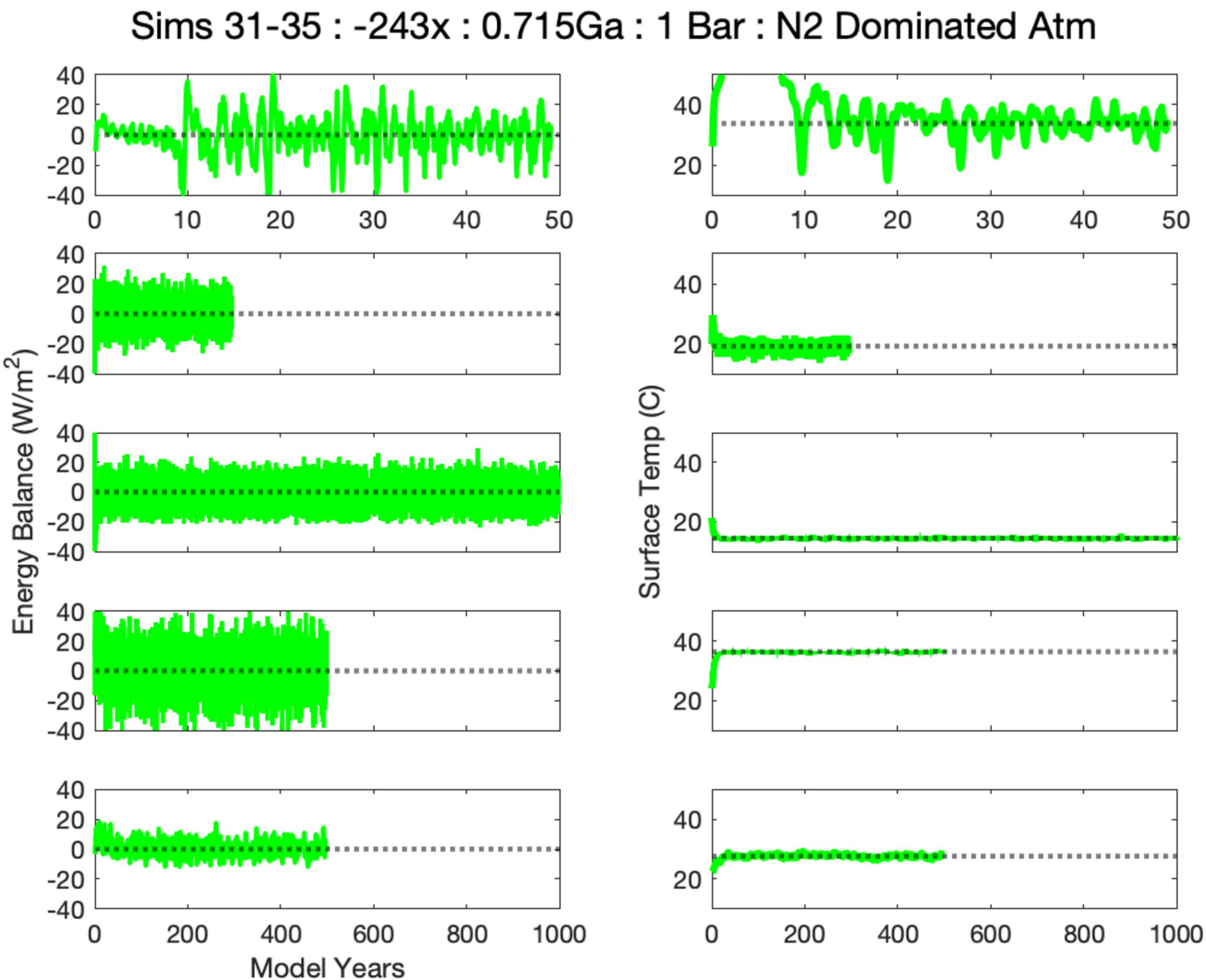

Sims 31-35 : -243x : 0.715Ga : 1 Bar : N2 Dominated Atm
Energy Balance (W/m2)
Surface Temp (C)
Model Years

Figure 9h.

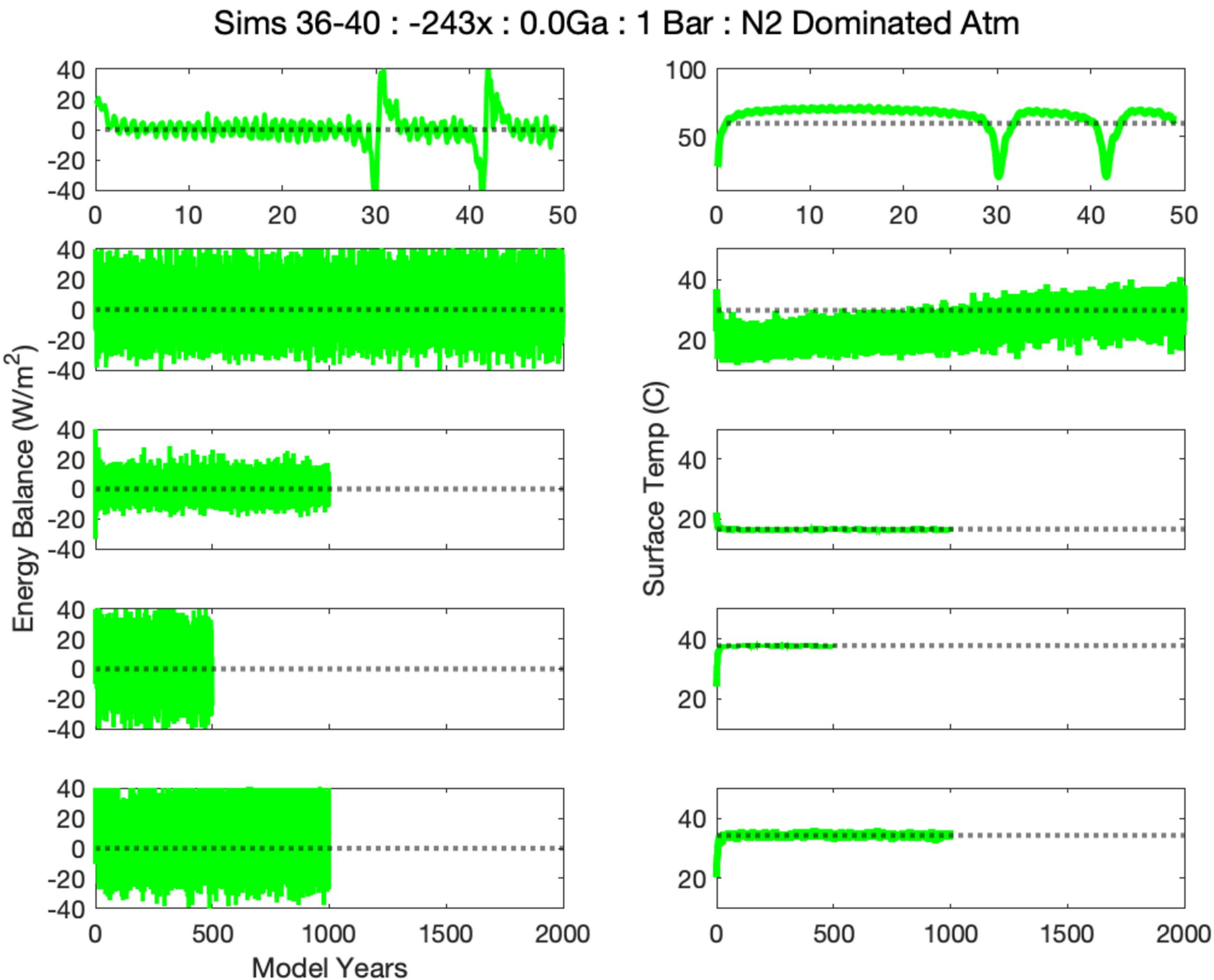
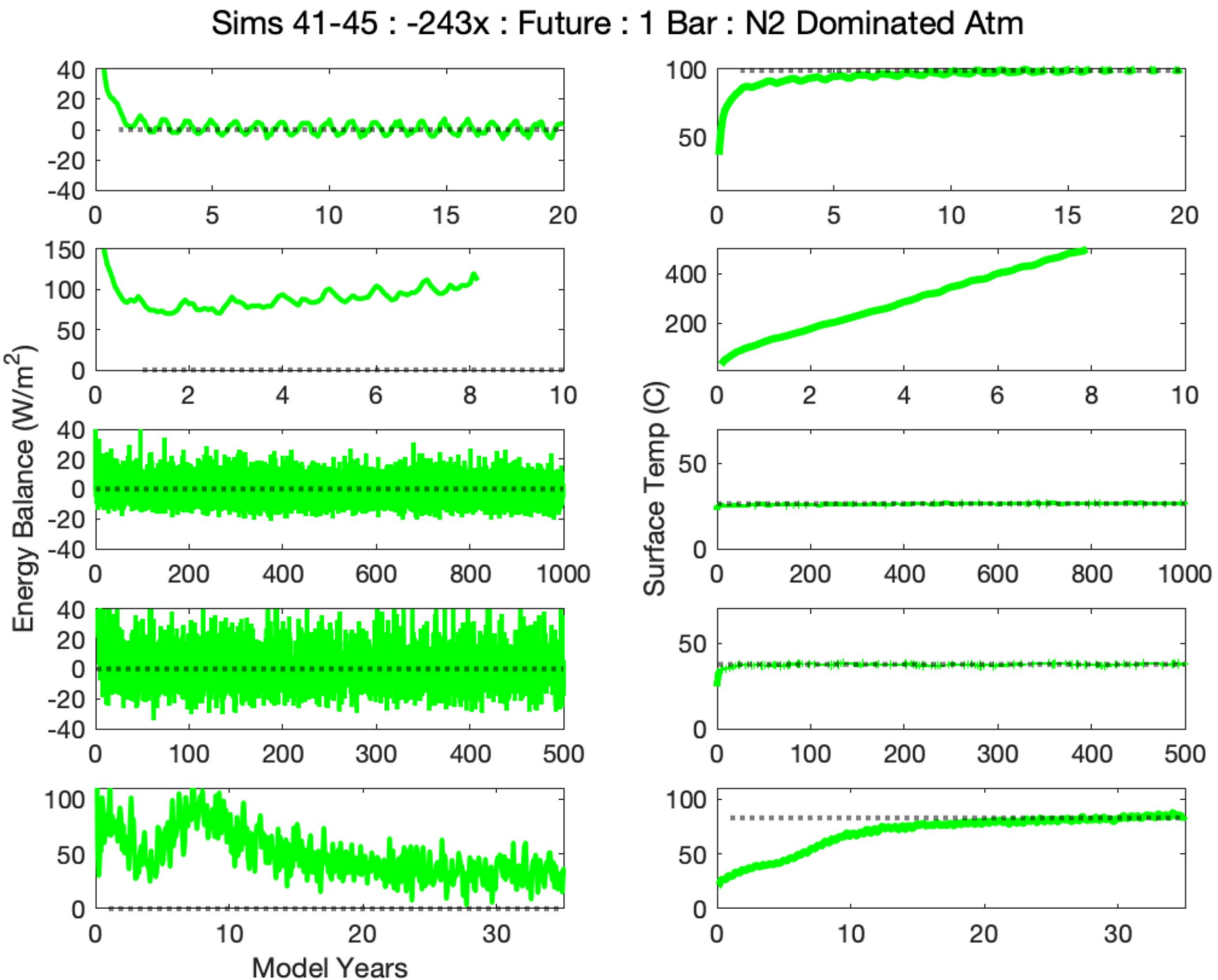

Sims 36-40 : -243x : 0.0Ga : 1 Bar : N2 Dominated Atm
Energy Balance (W/m²)
Surface Temp (C)
Model Years

Figure 9i.


Sims 41-45 : -243x : Future : 1 Bar : N2 Dominated Atm
Energy Balance (W/m2)
Surface Temp (C)
Model Years