Possible climate histories of Venus type worlds.  M. J. Way⁠¹ and A. D. Del Genio⁠¹, NASA Goddard Institute for Space Studies, 2880 Broadway, New York, New York, USA (michael.j.way@nasa.gov)

Introduction: There are two well-known scenarios for Venus’ climate evolution. In one Venus had a long-lived magma ocean phase in its first 100 Myr with a steam and CO₂ dominated atmosphere [1]. The faint young sun with its high XUV flux would cause photodissociation of the steam atmosphere and hydrodynamic escape would cause most of the hydrogen to escape and the left over oxygen would be absorbed by the magma ocean. Hence Venus would have started out hot and dry and the high D/H ratio measured by Pioneer Venus [2] would be from this period of water loss. The other scenario is that Venus’ magma ocean lifetime would have been roughly the same length of time as Earth’s (~1 Myr) and water would have condensed on its surface in its early history. As long as Venus remained in the slowly rotating climate dynamics regime [3,4] its cloud albedo feedback would have kept it temperate for possibly billions of years. The only way to confirm which one of these scenarios occurred for Venus is to visit it and make the necessary measurements of noble and volatile gases [5]. But exoplanet observations of young exo-Venus type worlds around young F,G,K dwarf stars may constrain whether both scenarios are equally probable for a population of such planets. We present a vision of Venus’ climate history that places it and its exo-Venus cousins in an ‘Optimistic Venus Zone’ within the conventionally named ‘Venus Zone’ [6] and hence encourage the exoplanet community to seek out these worlds as possible habitable environments.

Methods: We use ROCKE-3D, a three-dimensional general circulation model [7] to model 4 different types of topographies & water inventories (see Figure 1):

1) Arid-Venus: Modern Venus topography with 20 cm of water stored in the soil at model start. One can think of this as a Dune type world.
2) 10m-Venus: Modern Venus topography with 10m water equivalent layer placed in the lowest lying topographic regions at model start. See top image in Figure 1.
3) 310m-Venus: Modern Venus topography with 310m water equivalent layer placed in the lowest lying topographic regions at model start. See middle image in Figure 1.
4) 310m-Earth: Modern Earth type topography and land sea mask with a 310 meter deep bath-tub ocean. See bottom image in Figure 1.

These water inventories fit within the error estimates of the Pioneer Venus D/H ratio measurements [2]. We then model several different atmospheres at different time-slices. 10Bar CO₂ dominated at 4.2 Ga, 1 Bar CO₂ dominated at 4.2 Ga, 1Bar N₂ dominated (modern Earth like composition) at 2.9 Ga, 0.25Bar N₂ dominated at 2.9 Ga, 1Bar N₂ dominated at 0.715 Ga, Present day, and several Gigayear into the future (Figure 2). We use present day rotation rate & obliquity for all simulations in Figure 2.

Results: Figure 2 shows a sketch of our final results. Each error bar contains the mean surface temperature of the four different topographies mentioned in the Methods section. The 10bar atmosphere at 4.2 Ga has surface temperatures over 120°C, but the higher pressure means that surface liquid water can still condense on the surface. The 1 bar CO₂ atmospheres at 4.2 Ga are warm, but none are over 90°C. We then assume that a carbonate-
The silicate cycle begins to work (as it did in early Earth’s history) and N\textsubscript{2} dominated atmospheres (akin to that of modern Earth) take over sometime between 4.2 and 2.9Ga. We also include 1 set of simulations at 2.9Ga with 0.25Bar atmospheric density. This is inspired by atmospheric proxies in Earth’s Archean epoch [8,9]. As one can see these cases are much cooler and there are grid cells with subzero temperatures. Going forward in time it is clear that the mean surface temperatures remain moderate even with insolations more than double that received by modern day Earth. This implies that it is not the increase of solar insolation through time that may have changed Venus’ climate from temperate to its current hothouse state. We speculate that it was a series of simultaneous Large Igneous Provinces (i.e. The Deccan or Siberian traps on Earth) that would have loaded the atmosphere with large amounts of CO\textsubscript{2}. This would have increased surface temperatures and boiled off any shallow ocean, shutting down subductive plate tectonics and associated weathering processes. CO\textsubscript{2} would eventually become the main outgassing component as described in [10]. This scenario also fits in nicely with recent work by [11] that shows the timescale for a transition from a mobile to a stagnant lid plate tectonics would take ~1Gyr. This may imply a connection with the age of 80% Venus’ surface being ~750Myr old.

**Exoplanet Connection:** We would like to emphasize that if this “optimistic” scenario for Venus is correct then we should be cautious about concluding that extrasolar planets in the ‘Venus Zone’ outside the conventional ‘Habitable Zone’ are uninhabitable [6]. Hence we stress the need to search for young Venus type worlds around F, G and K dwarf stars (it is difficult to make the necessary observations of young exo-Venus’ around M-dwarfs due to their activity) to see if they indeed retain a steam atmosphere for ~100Myr. If not, and they are slow rotators (sidereal day lengths of 64 Earth days or longer) they may indeed host clement conditions despite residing well inside the traditional habitable zone.

**Figure 2:** Possible climate evolution of Venus. Each error bar contains the mean surface temperatures for each topography mentioned in the Methods section.

**References:**