The Long-term Evolutionary History of Venus' Climate & Applications to Exovenus Worlds. M. J. Way[1,3] and A.D. Del Genio[2], [1]NASA Goddard Institute for Space Studies, New York, New York, 10025, USA (michael.way@nasa.gov), [2](anthony.d.delgenio@nasa.gov), [3]Theoretical Astrophysics, Department of Physics & Astronomy, Uppsala University, Uppsala SE-75120, Sweden

Introduction: The long-term evolutionary history of Venus' climate largely remains a mystery. This is because much of its ancient surface remains hidden to us and there is a lack of in-situ noble gas isotope measurements to constrain it's water history. At the same time the work of [1] demonstrates two possible early evolutionary pathways. In the first scenario (Type 1) the surface of Venus' magma ocean crystallizes on a time scale similar to that of Earth's (approx. 10^6 years). This makes it possible to condense water on the surface of a cooled crystallized crust. In the second scenario (Type II) Venus loses all of its primordial water in its early history because of a long-lived magma ocean and steam atmosphere whose primordial water is mostly lost to space. However recent work by [2] shows that a large fraction of Earth's present day water inventory may have come from the LHB and Late Veneer, and the same could have been true for Venus. Hence if Venus starts out as Type II but the magma ocean crystallizes by the time of the LHB and Late Veneer it still may have had enough condensable water on its surface for a shallow ocean and a habitable climate like that shown in [3]. A caveat to this scenario is that its primordial rotation rate was slower than a 16 day long Earth sidereal day. A slow rotation rate early in its history may also be bolstered by recent work [4] showing that a shallow ocean may slow the rotation rapidly (of order millions of years) due to ocean tidal friction in the same way recent work has shown that modern Venus' atmosphere acts on its solid body to change its rotation rate [5].

Methods: We have completed an ensemble of simulations using ROCKE-3D [6] a 3-D General Circulation Model. The simulations include four topography types: a.) Modern Venus Topography with a 310m water equivalent layer (WEL) deep ocean b.) Modern Venus Topography with 10m WEL spread in the lowest lying basins c.) Modern Earth Topography with a 310m deep ocean d.) An Aquaplanet of 158m depth. Each of these 4 simulations were run at 3 different epochs: 4.2 Giga-years ago (Gya), 0.715Gya and present day. These correspond to present day Earth insolation (1361 W/m^2) multiples of 1.4, 1.71 and 1.9. All use modern Venus orbital parameters and rotation rate. All atmospheres are 1bar pressure. However, the 4.2Gya simulations atmosphere consists of 90% CO_2 and 10% N_2, while those at 0.715 and present day utilize a modern Earth-like N_2 dominated atmosphere with 400ppmv CO_2 and 1ppmv CH_4. See Table 1. The rationale for these choices are informed by how we think the Earth's atmosphere may have evolved over the past 4Gy; starting out with a CO_2 dominated atmosphere and becoming N_2 dominated via the carbonate-silicate cycle.

Results: A sketch of the simulation results for the global mean temperature as a function of insolation/time are shown in Figure 1. The take-away message is simple: why doesn't present day Venus have a mean surface temperature in the range of ~20-40C? Our hypothesis is that Venus may have had a stable climate for billions of years with a carbonate-silicate cycle similar to that of Earth. It is possible that the near-global resurfacing we see today that took place approximately 750Mya is responsible for its present day climate. Major overturn events, or a proliferation of Large Igneous Provinces over millions of years [7,8] could have turned Venus' once stable temperate climate into the CO_2 dominated hot house of today.

References: [1] Hamano et al. 2013 Nature 497, 607 [2] Greenwood et al. 2018, Sci Adv 4, eaao5928 [3] Way, M. J., et al. (2016) GRL, 43, 8376-838 [4] Green et al. 2018, AGUFM, P31E-3749 [5] Navarro T, Schubert G, Lebonnois S. 2018. *NGeo*. 2, 1 [6] Way, M.J. et al. (2017) ApJS, 231, 1 [7] Ernst, R.E. et al. LPSC 48, 1373 [8] Ernst R.E. & Desnoyers D.W. 2004, PEPI 146, 195.

Table 1:

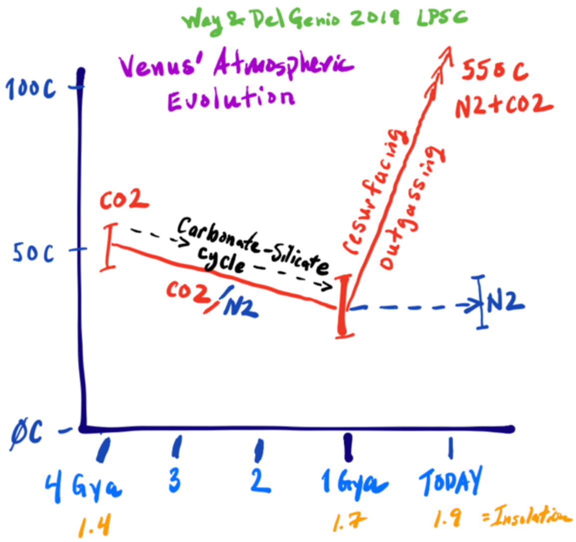
Sim	S0X/Epoch[a]	Topo/Atmosphere[b]	Temp[c]
A	1.4/4.2Gya	Venus-310m/CO_2-N_2	56C
B	1.4/4.2Gya	Venus-10m/CO_2-N_2	44C
C	1.4/4.2Gya	Earth-310m/CO_2-N_2	45C
D	1.4/4.2Gya	Aqua-900m/CO_2-N_2	23C
E	1.7/0.7Gya	Venus-310m/N_2	14C
F	1.7/0.7Gya	Venus-10m/N_2	19C
G	1.7/0.7Gya	Earth-310m/N_2	15C
H	1.7/0.7Gya	Aqua-900m/N_2	37C
I	1.9/0.0Gya	Venus-310m/N_2	17C
J	1.9/0.0Gya	Venus-10m/N_2	34C
K	1.9/0.0Gya	Earth-310m/N_2	35C
L	1.9/0.0Gya	Aqua-900m/N_2	38C

a: S0X=multiple of present day Earth insolation (S0X=1=1361W/m^2)

b: CO_2-N_2 = 90% CO_2, 10% N_2. N_2 = N_2 dominated with 400ppmv CO_2, 1ppmv CH_4.

c: Temp=Global Mean Surface Temperature for 1/6th of a diurnal cycle.

Figure 1:


Way & Del Genio 2019 LPSC
Venus' Atmospheric Evolution
100C
50C
ØC
CO2
Carbonate-Silicate cycle
CO2/N2
resurfacing
outgassing
550C
N2+CO2
N2
4 Gya
3
2
1 Gya
TODAY
1.4
1.7
1.9
=Insolation