Lecture 1: Venus A. P. Ingersoll api@gps.caltech.edu

1. Three topics: (1) An ocean of air: The average pressure at the surface of Venus is 92 bars. The Earth's oceans spread across the planet would be ~300 bars. What does this mean for the meteorology? (2) The runaway greenhouse – why is there so little water on Venus today? (3) The super-rotation – At the tropopause, the atmosphere spins 50 times faster than the solid planet. How is this maintained?

2. Basic facts about the Earth and Venus. We infer the size of the core from the bulk density. Other quantities have been measured. The similarities have lead to calling Venus the Earth's sister planet, but it would be a hellish place to live. [A. Ingersoll, Nature News and Views 450, 617-618 (2007)]

3. The atmosphere is 96.5% CO_2 and 3.5% N_2 , with small amounts of Ar, CO, H_2O, and O_2. The total CO_2 on Venus is only slightly greater than the CO_2 locked up in limestone on Earth. The total N_2 on Venus is only slightly greater than the total N_2 on Earth. Water is totally different, suggesting it was lost. [Planetary Sciences, I. de Pater and J Lissauer (2001)]

4. The clouds are made of sulfuric acid droplets about r = 1 micron in size. The atmosphere and planet rotate opposite to the orbital motion - clockwise as viewed from above the solar system, which is opposite to the Earth. [NASA photo]

5. The surface is hot and dry, with very little evidence of erosion. [NASA]

6. Temperature mostly follows a dry adiabat, although there is a stable layer in the 40-50 km range. The sulfuric acid clouds block the escaping IR radiation, so convection has to carry the heat through the clouds. This creates an adiabatic layer from 50-60 km. Radiation to space occurs at ~65 km altitude. [Seiff, in Venus, Hunten etal, Ed., U Arizona Press (1983)]

7. The clouds are near the 1 bar level on both planets. The atmosphere below the clouds is clear. Some sunlight reaches the ground. On Earth, no sunlight reaches the bottom of the oceans, which is a major difference in the dynamics. [A. Ingersoll, Nature News and Views 450, 617-618 (2007)]

8. Basic meteorology of Earth. Excess absorbed sunlight at the equator and excess emitted longwave radiation at the poles requires poleward heat transport by the ocean and atmosphere. The transfer of energy is not complete, because the poles are still much colder than the equator. The emitted longwave is less at the poles because they are colder.

9. The ocean and atmosphere play almost equal roles. The atmosphere is more important at high latitudes.

10. The emitted longwave is almost flat at Venus, indicating that the poles are almost as warm as the equator. The deep atmosphere of Venus is more effective than the deep oceans of Earth because the deep atmosphere is stirred by convection, since some sunlight reaches the surface. [F. W. Taylor in Venus, U Arizona Press (1983)]

11. Here is a one-parameter model of the runaway greenhouse: The tropopause temperature and the emitted longwave radiation increase together when the atmosphere is cold (left side of the curve). Then there is a maximum in the emitted longwave flux, because the denominator increases faster than the numerator. Further increase in the tropopause temperature puts more water vapor into the stratosphere, which blocks the emitted longwave radiation, and the flux decreases. K is the absorption coefficient of water vapor and μ is the relative humidity. The Earth emits about 240 W m^{-2}. If you moved Earth to the orbit of Venus it would have to emit twice that amount, and it can't do it as long as μ is close to 1.0. You have to boil the oceans to get μ to values less than 1.0. [Nakajima etal, J. Atmos. Sci, 49, 2256-2266 (1992)]

12. Here's a better theory: It's not just the stratosphere that matters. If the troposphere can't deliver the IR radiation to the base of the stratosphere, then the maximum flux to space is even smaller. One estimate is 293 W m^{-2} which is very close to the Earth's present value of 240 W m^{-2} . [Nakajima etal]

13. Here's an even better theory, taking into account all the non-grey radiative transfer and the moist and dry adiabatic lapse rates. The transition is at 293 W m^{-2} . Above this point, the temperature at the surface goes up to 1600 K and the pressure goes up to greater than 100 bar. [Abe and Matsui, J. Atmos. Sci, 45, 3081-3101 (1988)]

14. The height of the tropopause goes up to 300 km, and water vapor is the main constituent of the atmosphere. The tropopause is not much warmer than the current tropopause of Earth, but the pressure of other gases like N_2 is much less at the tropopause. These authors were thinking of early Earth when the solar constant S_0 was less and there was an additional heat flux F_0 due to impacts.

15. These are moist adiabats. The current Earth has water vapor/nitrogen $\sim 10^{-2}$ at the surface and 10^{-6} at the tropopause (lower curve). A water vapor atmosphere has water vapor/nitrogen greater than 1.0 at all levels (upper curve). This is important, because nitrogen and oxygen act as a radiation shield that protects the water vapor from ultraviolet light. Without this radiation shield, in a water vapor atmosphere, the water will be turned into H and O. The H will escape into space, and the oxygen will combine with C and Fe in the surface rocks. Pretty soon all the water will be gone. [Ingersoll, J Atmos. Sci 26, 1191-1198 (1969)]

16. Evidence that this might have happened is found in the heavy isotope of hydrogen – deuterium. Venus is off scale. The lighter H escapes faster, leaving the D behind, and the D/H ratio increases with time. The current D/H is 150 times the Earth's value, which is higher than anything else in the solar system. [de Pater and Lissauer, Planetary Sciences, Cambridge University Press, 2001]

17. Venus Express found that the D/H is 300 times the Earth's value in the upper atmosphere, indicating that this fractionation process is operating today. [Bertaux, Nature 450, 646-649 (2007)]

18. Here's another picture of the sulfuric acid clouds. Now we talk about the circulation of the atmosphere.

19. The wind profile. Remember they are blowing to the west. Let's use the words prograde and retrograde for winds blowing in the same or opposite to the planet's rotation. The Earth's tropospheric jet streams have a speed of 40 m s^{-1}, which is also the speed of a typhoon. The jet streams on Earth are prograde. [Schubert, in Venus, Hunten, Ed., University of Arzona Press, 1983]

20. There is some confusion about east and west. The winds are prograde; they blow in the same direction as the spin of the planet, which is opposite to the spin of the Earth. These are winds at cloud top level, measured by tracking clouds in series of images. The meridional wind at cloud top level is from the equator to the pole in both hemispheres. [Gierasch etal, in Venus II, Bougher etal, Eds. U Arizona, 1997]

21. Buoyancy frequency (Brunt frequency) squared = N^2 . Notice the stable region from 40-50 km. Neutral stability (convection) above and below. [Gierasch etal]

22. This model reproduces the zonal wind with maximum speed of 100 m s^{-1}. [Yamamoto and Takahashi, J. Atmos. Sci 60, 561-574 (2003)]

23. Rising motion at the equator, sinking motion poleward of 35 degrees. Poleward flow (not shown) agrees with cloud tracked meridional winds. This mean meridional circulation (MMC) brings air with high angular momentum (AM) per unit mass up at the equator and sends air with low AM per unit mass down at the poles. [Figs. 22-26 are from Yamamoto and Takahashi]

24. Since the air is moving poleward in each hemisphere, it should conserve angular momentum, but it doesn't. Instead, it loses angular momentum to the eddies, which transport it toward the equator. You can see this in the tilt of the velocity vectors. Air moving toward the equator (left side) carries eastward momentum, and air moving away from the equator carries westward momentum. The net effect is to add eastward momentum to the equator and remove it from higher latitudes.
This is the Gierash mechanism for maintaining the super-rotation. The mean meridional circulation brings it up from below and the eddies bring it in from the higher latitudes.

25. This shows the same thing. The eddies make u'v' < 0 in the north and u'v' > 0 in the south.

26. This shows u'w' < 0, which means the vertical transport of AM is in the wrong direction to maintain the zonal flow. The u'w' term is downward, but not as large as the upward transport by the MMC.

27. An alternate view. These are tides driven by absorption of sunlight in the clouds , 60-65 km altitude. The slope of the phase lines means the tidal wave is has phase velocity upward and to the left (group velocity is downward and to the left). The jet is to the right (prograde) and the sun is moving to the left (retrograde). This means the tides are accelerating the flow in the clouds, which is the peak of the jet and helping to maintain the jet speed. [Tagaki and Matsuda, Geophys. Res. Lett. 33, L13102 (2006)]

28. The magnitude of the acceleration by this method is comparable to that by the Gierasch mechanism.

29. A question: Is there something analogous to the Quasi Biennial Oscillation (QBO)? Notice the descending pattern of easterlies and westerlies with a ~26 month period. Figure is from [Holton, Introduction to Dynamics Meteorology, 2004]

30. Cartoon of a theory of the QBO. Both easterly and westerly waves (± c) propagate up from the troposphere. The easterly waves (c <0) carry easterly momentum, and the westerly waves carry westerly momentum. Both waves dump their momentum when they propagate into a region that is moving as fast as the wave - a critical level. This brings down the easterly parts and the westerly parts of the zonal jets. The pattern descends. The 26 month period depends on how much momentum is carried by the waves. If the waves are energetic, the period is shorter. [G. Holton, Introduction to Dynamic Meteorology (2004)]

31. Phase diagram for Rossby waves, Rossby-gravity waves, and pure gravity waves. They are all trapped at the equator. The Kelvin wave moves the fastest, but it can only propagate to the east. The RGW and the KW carry westward and eastward momentum, respectively. [A Gill, Atmosphere-Ocean Dynamics, Academic Press, 1983]

32. One cycle of a Kelvin wave. The solid lines are pressure. The arrows are the wind vectors. Figures 32-35 are from [Holton]

33. Same for the RGW [Holton]

34. It's the tilt of the phase lines that matters. The eastward tilt with height means the Kelvin wave carries eastward momentum upward.

35. The RGW tilts to the west. Here it is not the tilt, but it is the northward transport of heat, which tends to accelerate the jet.