Venus Upper Atmosphere Investigations
Science and Technical Interchange Meeting

What We Know Today About the Venus Middle Atmosphere

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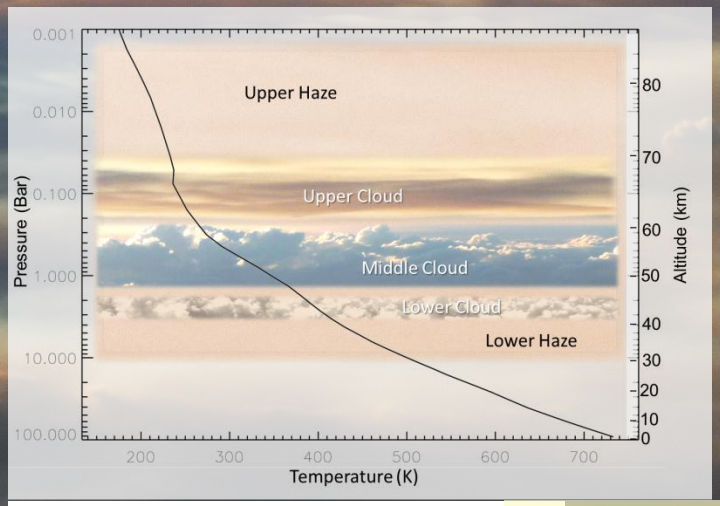
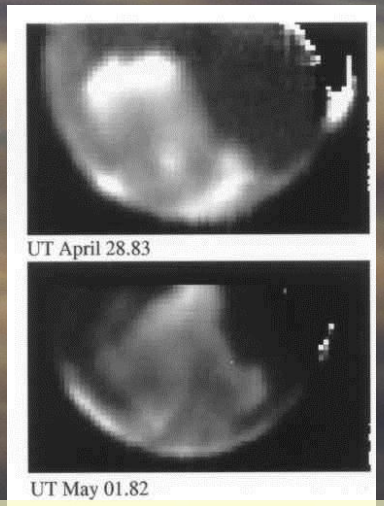
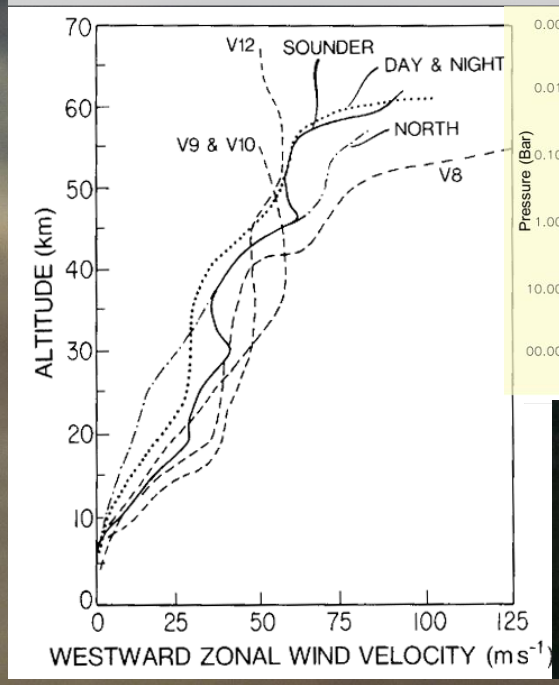
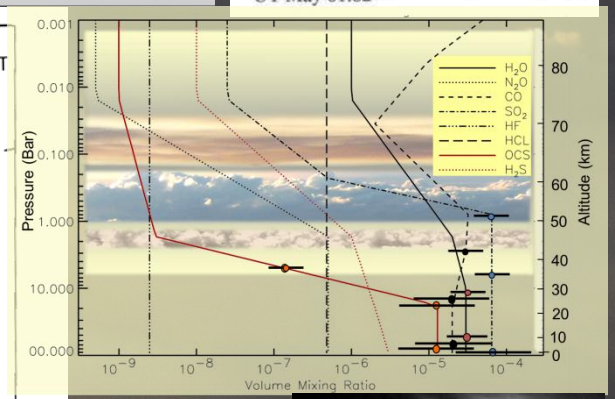
The Venus Atmosphere

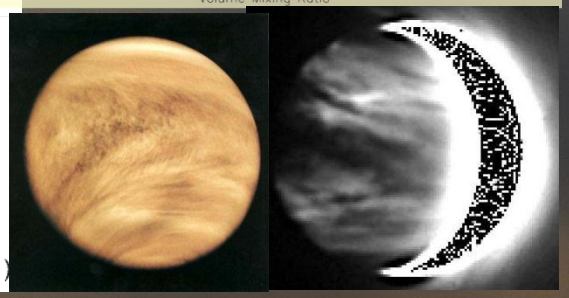
- Thermal Structure
  - Hot surface
  - Near adiabatic lower atmosphere
  - Warm polar mesosphere
- Composition
  - Trace gases and isotopes
  - Cloud processes
- Atmospheric Dynamics
  - Deep atmosphere circulation
  - Cloud-top superrotation
  - Mesospheric circulation
  - Thermospheric circulation
- Greenhouse Effects

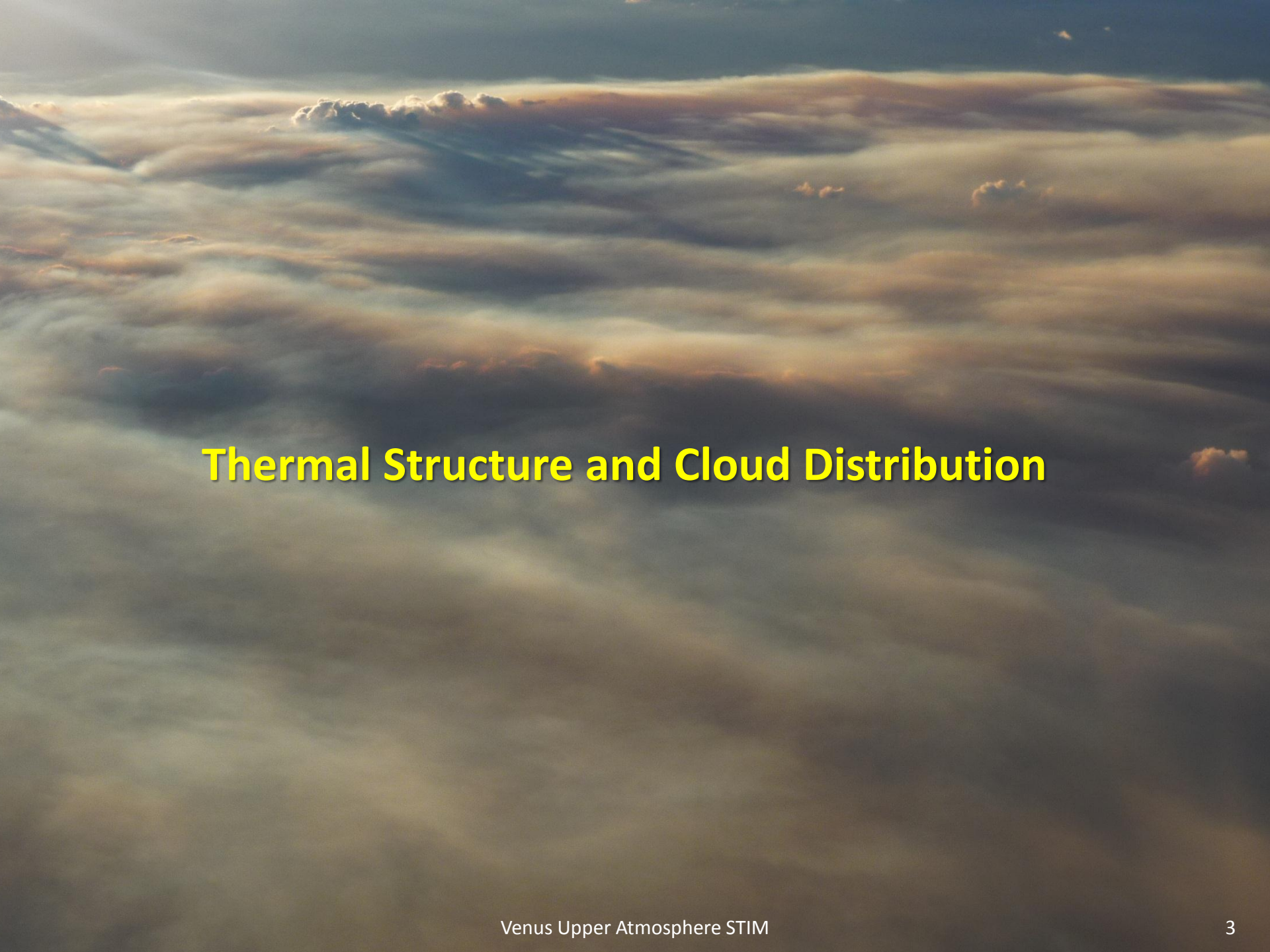






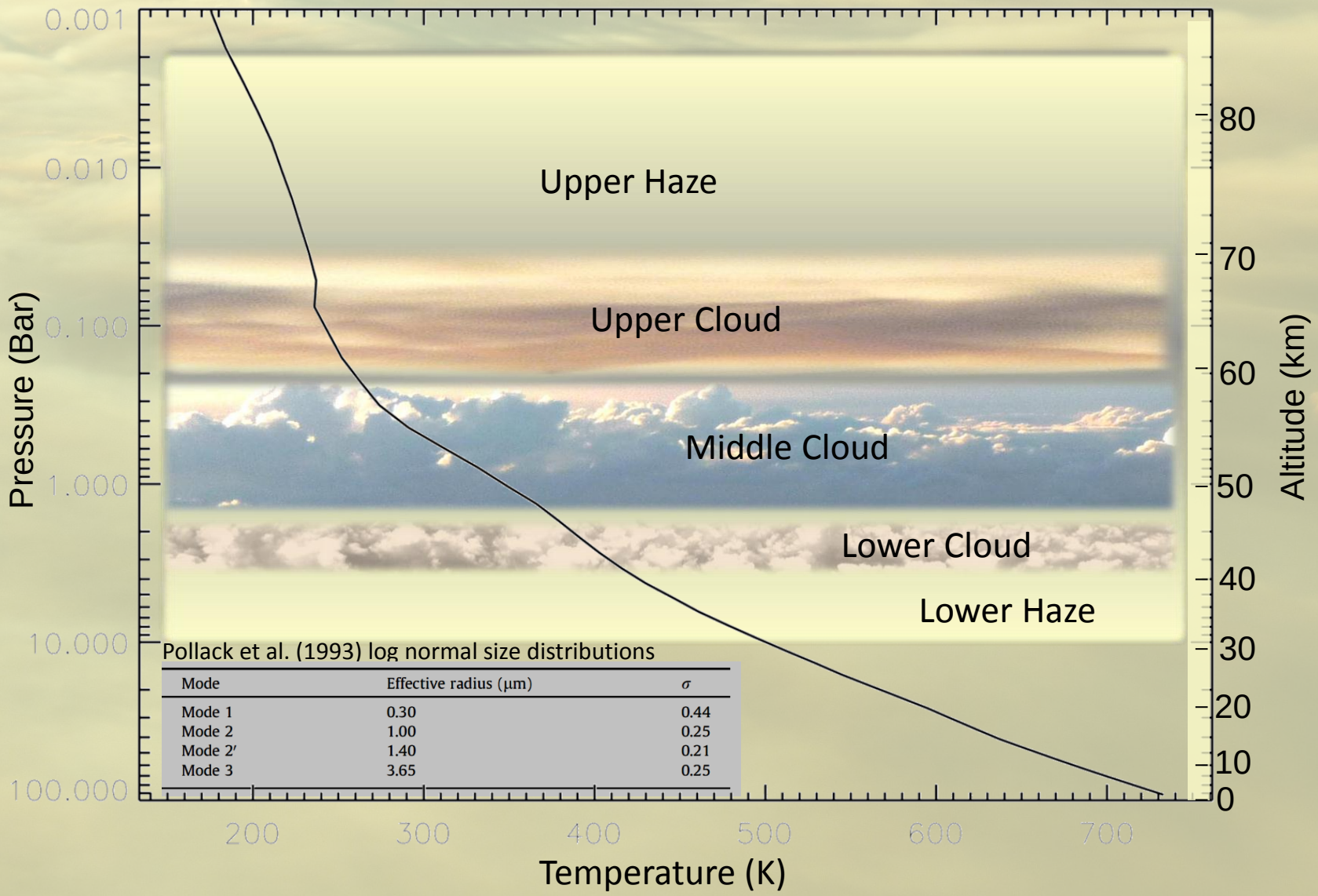






Thermal Structure and Cloud Distribution

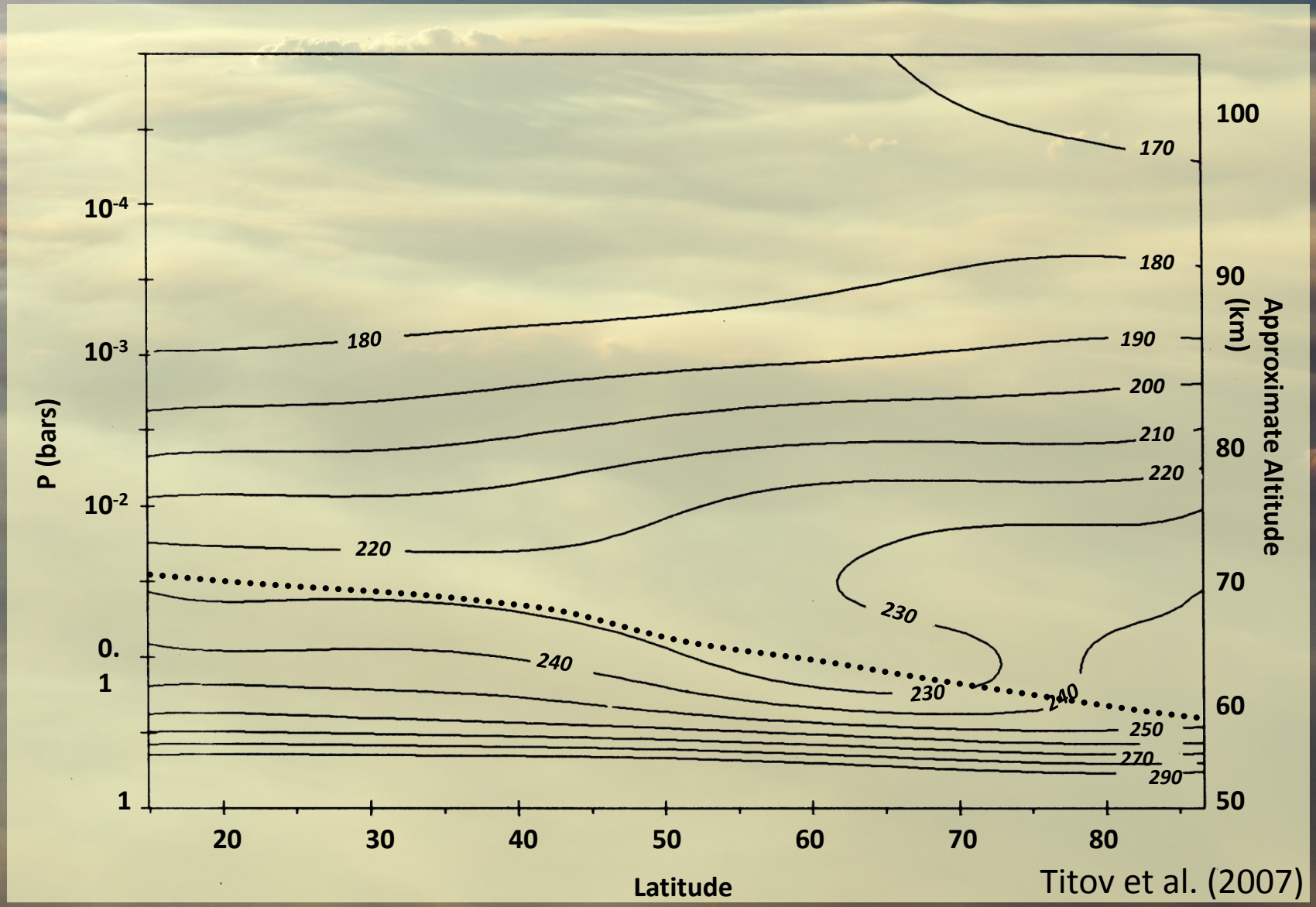
Mean Thermal Structure and Clouds



Pollack et al. (1993) log normal size distributions

Mode	Effective radius (μm)	σ
Mode 1	0.30	0.44
Mode 2	1.00	0.25
Mode 2′	1.40	0.21
Mode 3	3.65	0.25

Mesospheric Temperature Fields



Titov et al. (2007)

At altitudes between 70 and 100 km, temperature increase between the equator and pole. The dashed line shows the relative position of the cloud tops (visible optical depth = 1).

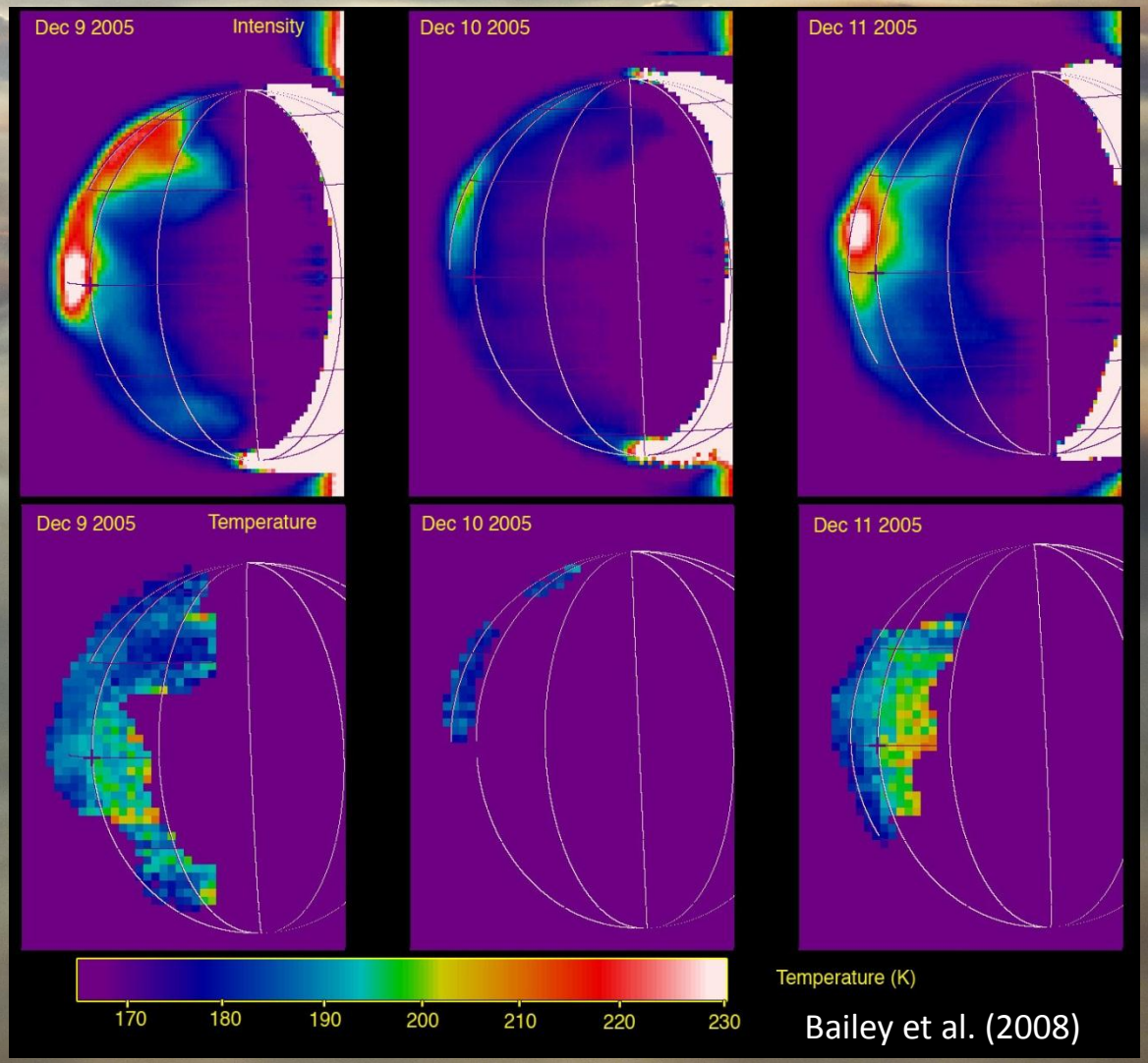
Variability of Upper Mesospheric Temperatures

Temperature measurements obtained at different times with different methods indicate significant variations in upper mesospheric temperatures. The mechanisms responsible for these changes are not well understood.

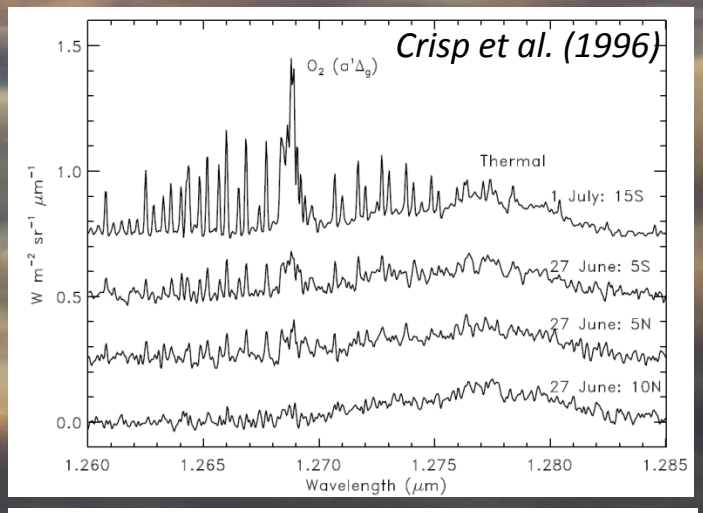
Method	Temperature (K)	Reference
1.27 mm O_2 airglow	185 ± 15	Connes et al., 1979
Pioneer Venus night probe deceleration	167.2	Seiff & Kirk, 1982
Pioneer Venus OIR	170-175	Schofield & Taylor, 1983
VIRA (based on OIR and probe deceleration)	168	Seiff et al., 1985
CO mm lines	165 – 210	Clancy & Muhlmann, 1991
1.27 mm O_2 airglow	186 ± 6	Crisp et al., 1996
CO mm lines	165 – 178	Clancy et al., 2003
1.27 mm O_2 airglow	193 ± 9	Ohtsuki et al., 2005
Venera 15 IR Fourier spectrometer	166.4	Zasova et al., 2006
SPICAV Stellar occultation	194 – 240	Bertaux et al., 2007
1.27 mm O_2 airglow (intensity weighted mean)	181 – 196	Bailey et al. 2008

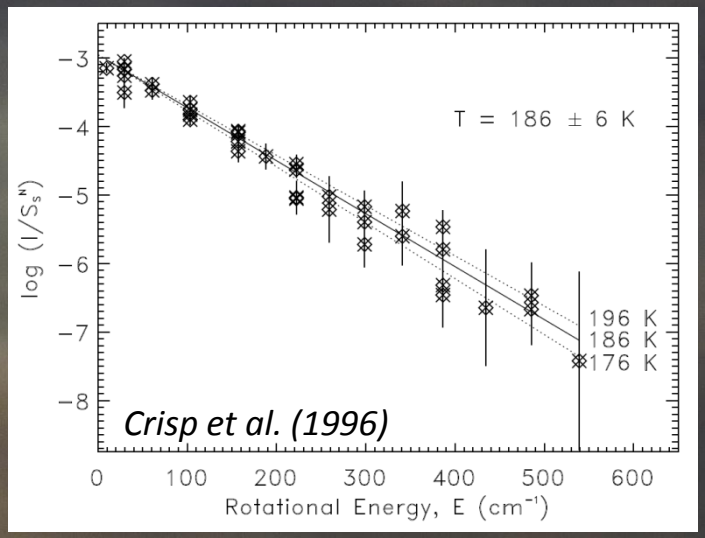
From Bailey et al. 2008.

Upper Mesospheric Temperature Variations



Bailey et al. (2008)





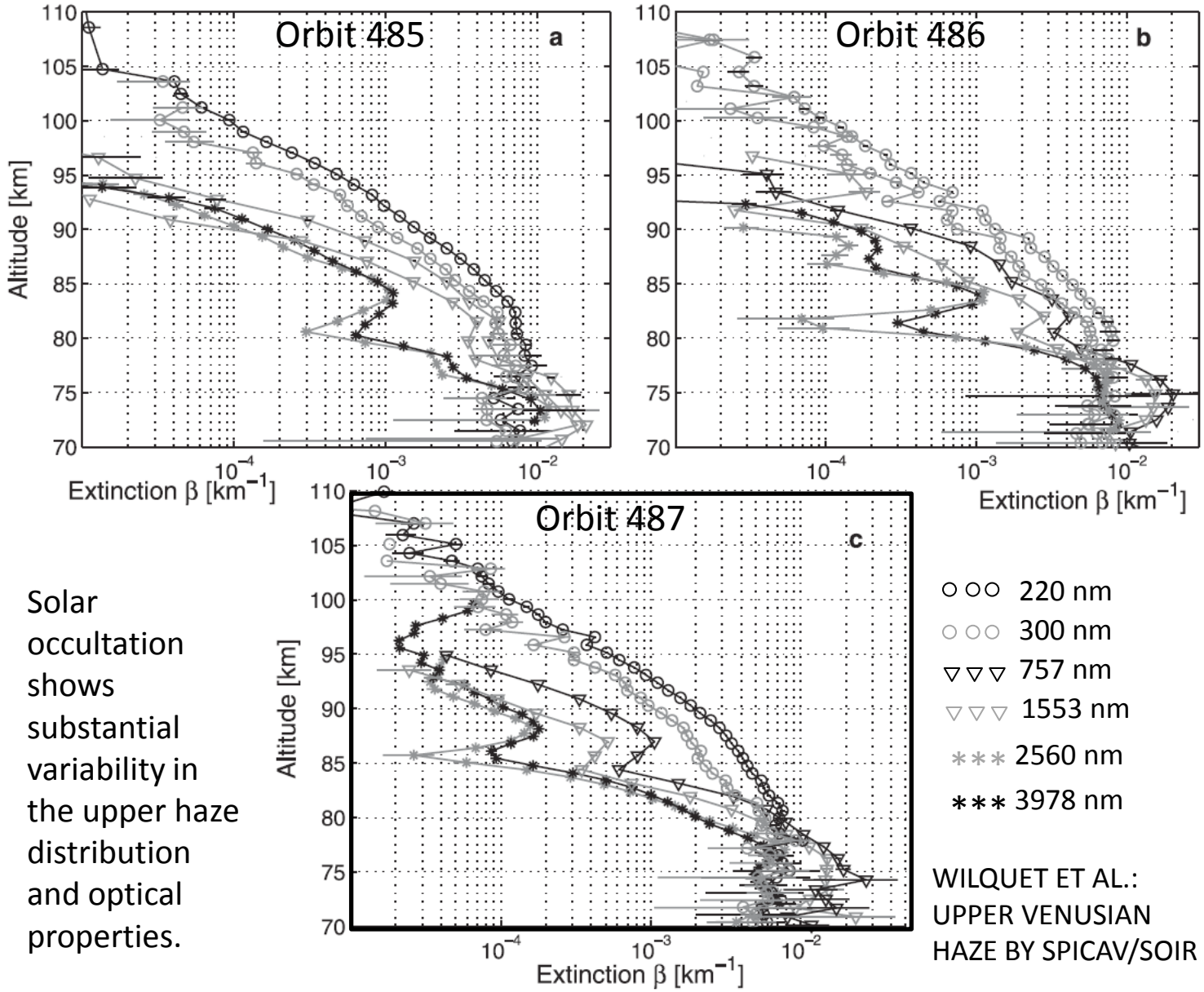
Temperatures in the upper mesosphere can be retrieved from rotational population of the O_2 $^1\Delta_g$ airglow lines. Surprisingly, these retrievals show little spatial correlation with the O_2 airglow emission.

The Venus Clouds

- What we think we know about the clouds
  - The main cloud deck extends from ~47 to 71 km altitude at low latitudes
  - The altitude of the cloud decreases with increasing latitude
  - Most measurements indicate that the main cloud deck consists of three distinct layers, separated by relatively clear regions near 49 and 58 km
  - These clouds are composed primarily of spherical, concentrated (75% – 95%) sulfuric acid particles with a range of particle sizes
  - A thin haze extends both above and below the cloud deck. Above the clouds, this haze is composed of 0.1 to 0.3 µm radius H_2SO_4 particles.

- A few things we don't know about the clouds
  - An unknown UV absorber is embedded within the upper cloud deck. It could be associated with absorbing particles or trace gases
  - The composition of the haze within and below the middle and lower clouds is consistent with H_2SO4, but is not known
  - The composition and phase of the large "Mode 3" particles is still not known
  - The physical processes that maintain the vertical structure of the clouds, and the three distinct cloud layers with gaps at 48 and 58 km are not well understood
  - The distribution of cloud forming gases (H_2O, SO_2) within the clouds is unknown

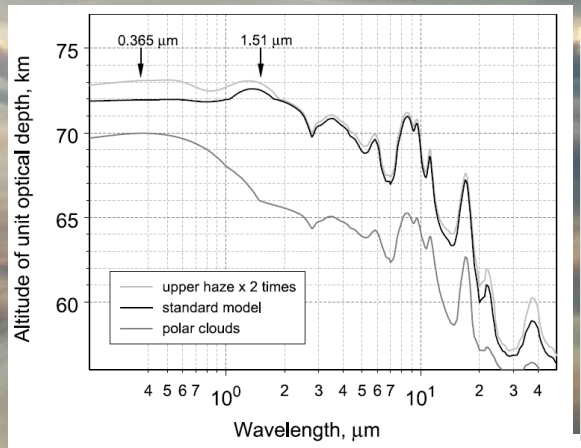
Variability in Upper Haze Extinction

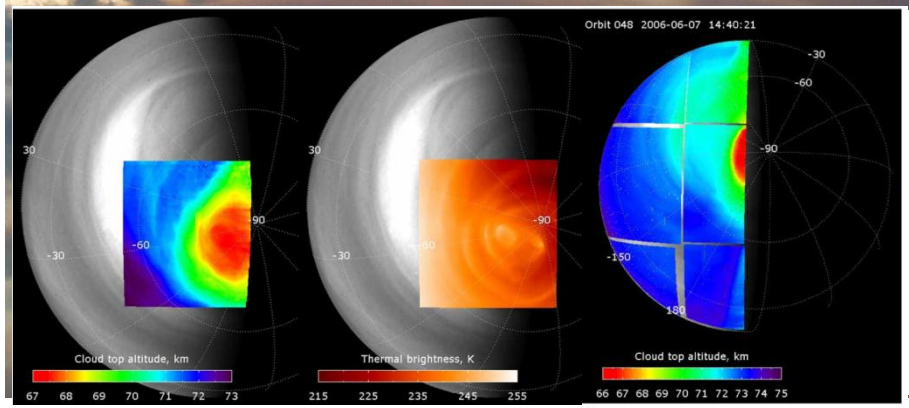


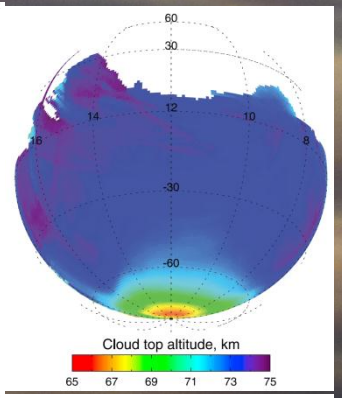
Solar occultation shows substantial variability in the upper haze distribution and optical properties.

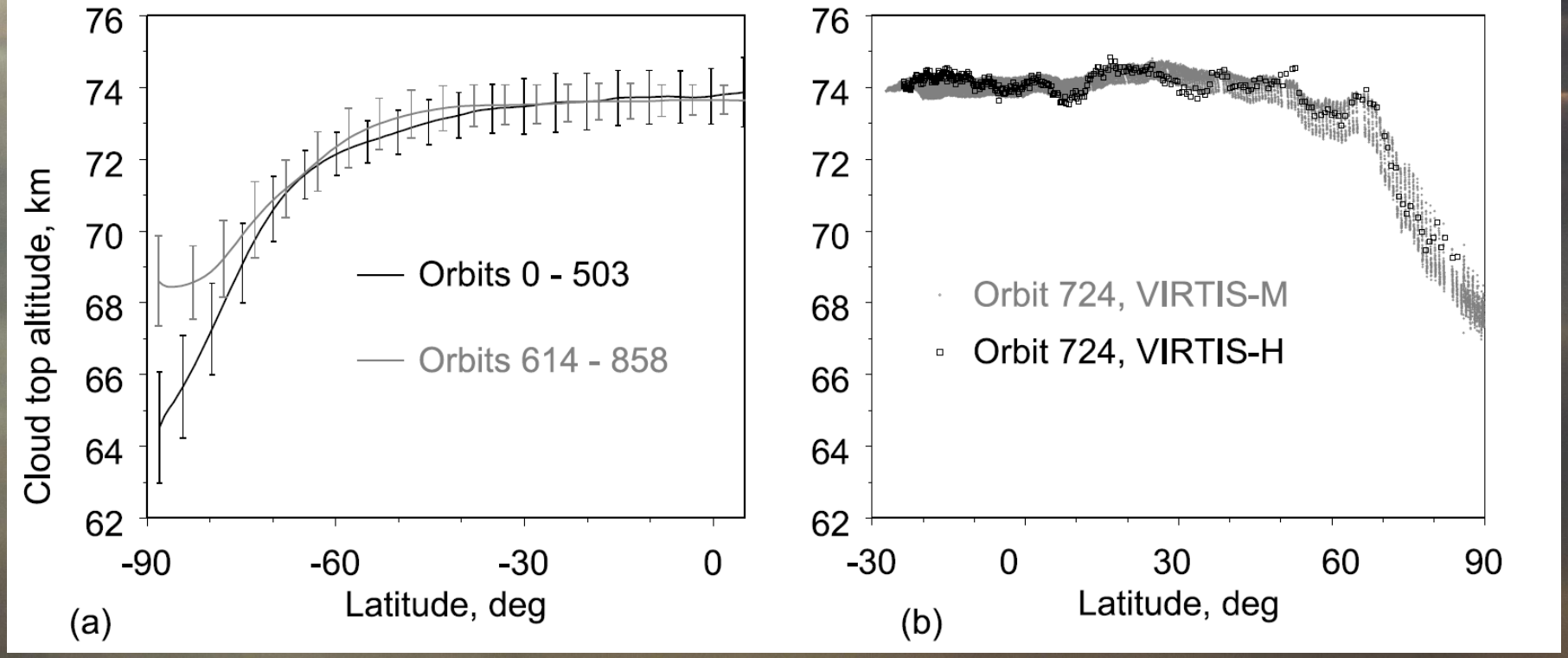
WILQUET ET AL.: UPPER VENUSIAN HAZE BY SPICAV/SOIR

Probing Cloud Top Altitudes



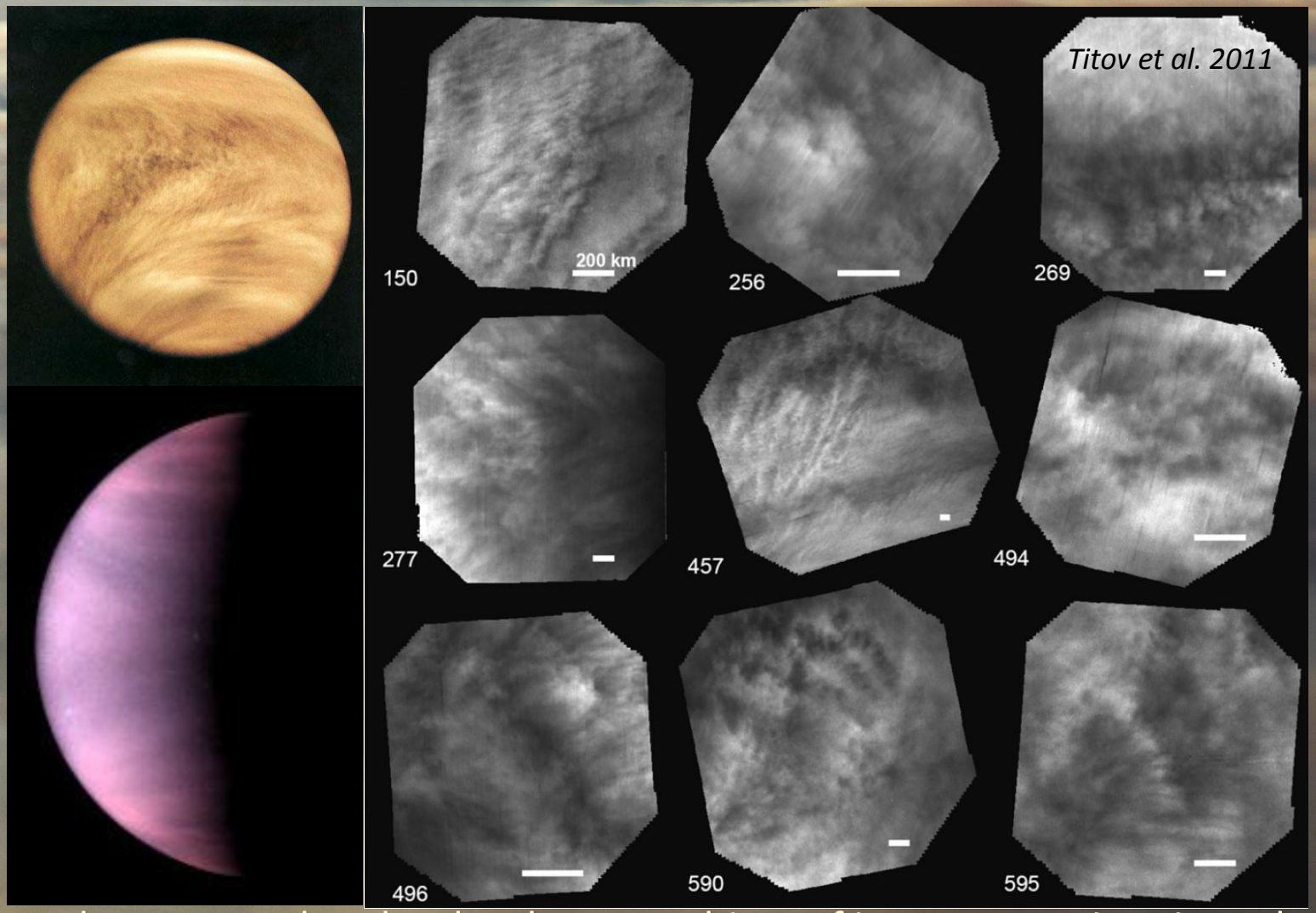






IGNATIEV ET AL. (2009): ALTIMETRY OF VENUS CLOUDS

The Cloud-top UV Absorber



The unknown UV absorber has been a subject of intense scrutiny since the dawn of the space age. Entry probe observations show that it is confined to the upper cloud, but provide little information about its nature or vertical distribution.

Pioneer Venus Cloud Particle Measurements

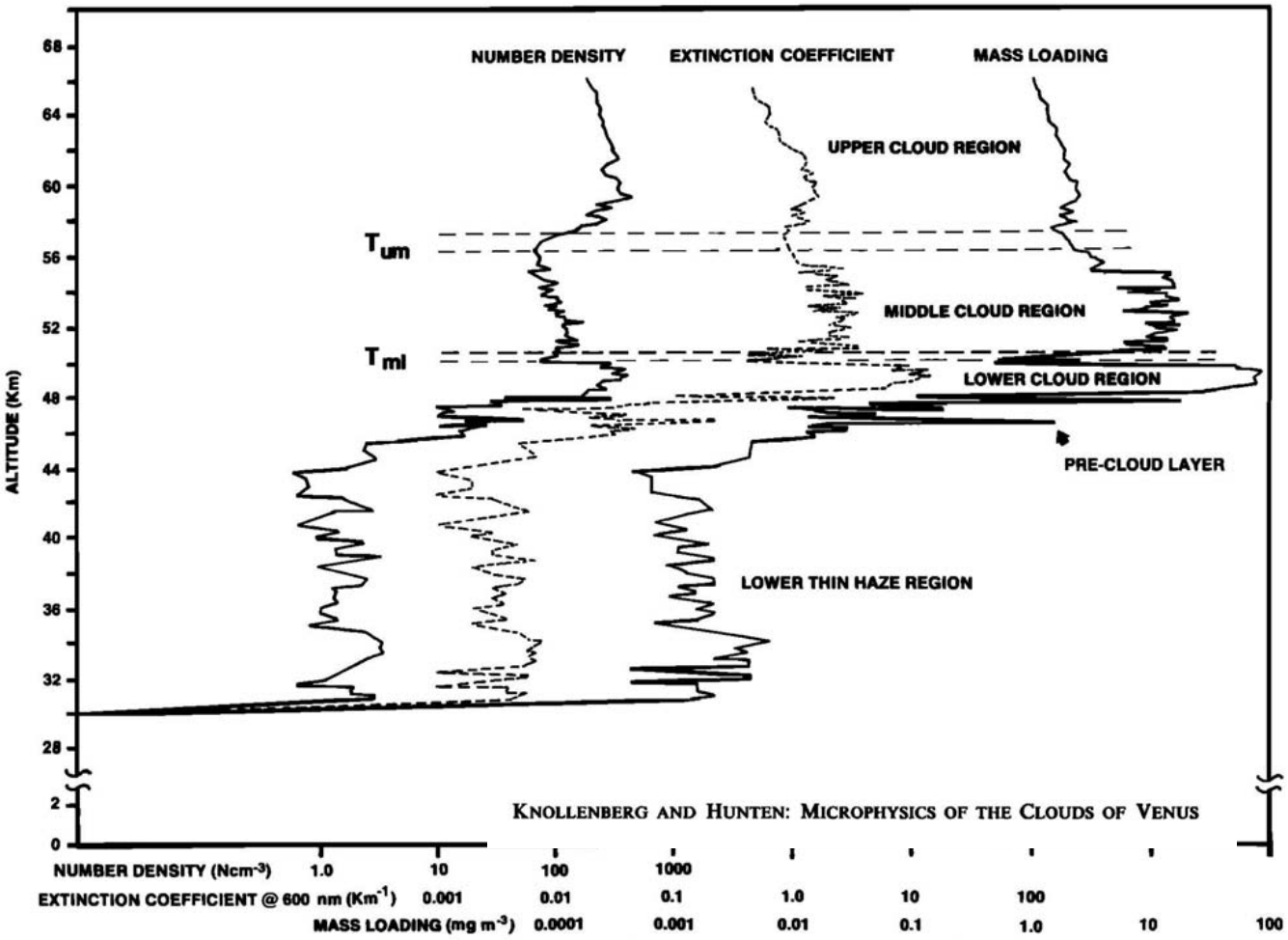
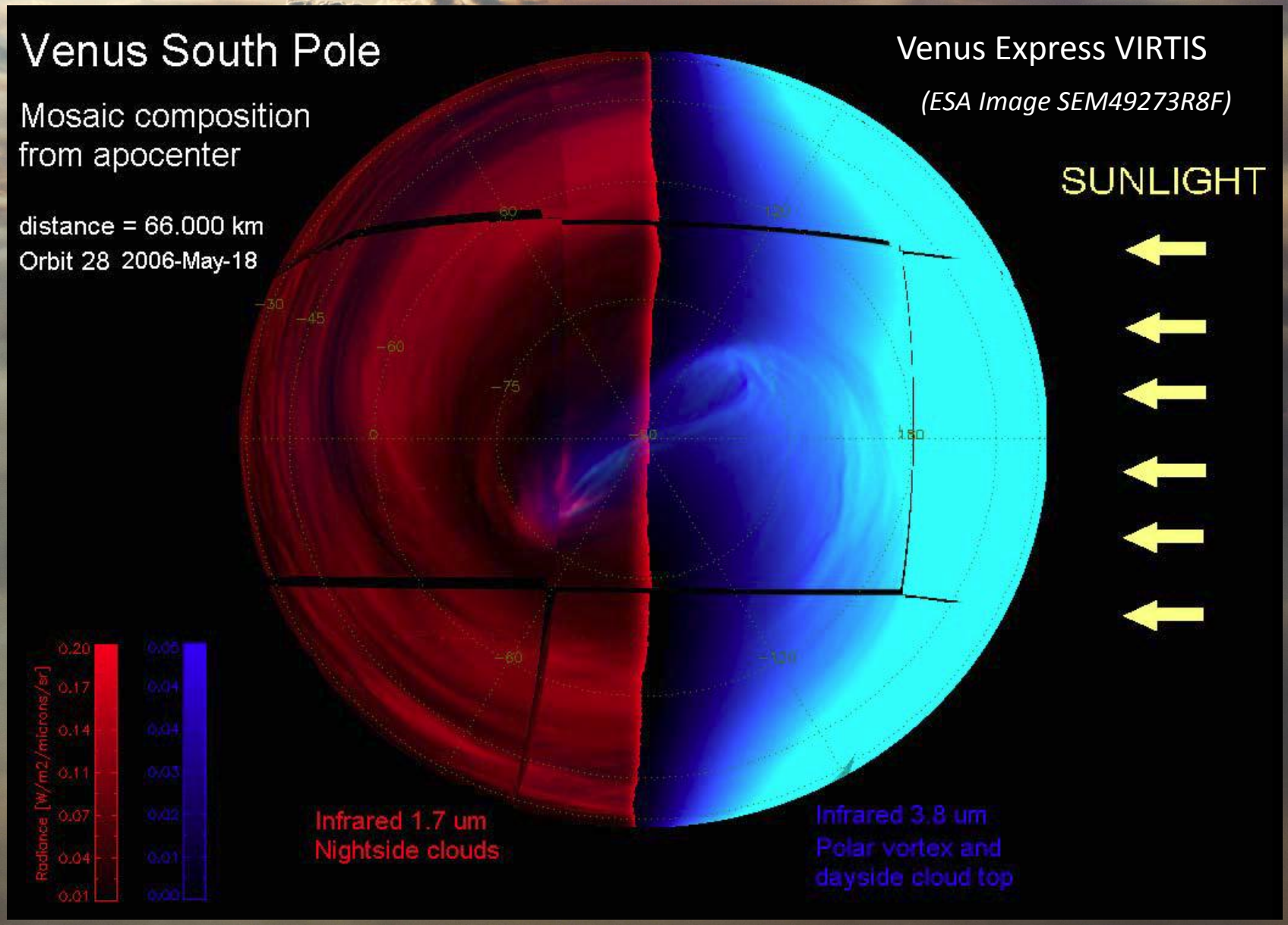


Fig. 4. Vertical structure of Venus cloud system. The above data represent direct computations from the LCPS data. No allowance has been made for particles smaller than the 0.6 μm lower limit of size sensitivity or above the largest sizes actually measured. A density of 2 g cm^{-3} was assumed for mass loading computations. The thickness of T_{um} is about 1 km while T_{ml} is several hundred meters thick.

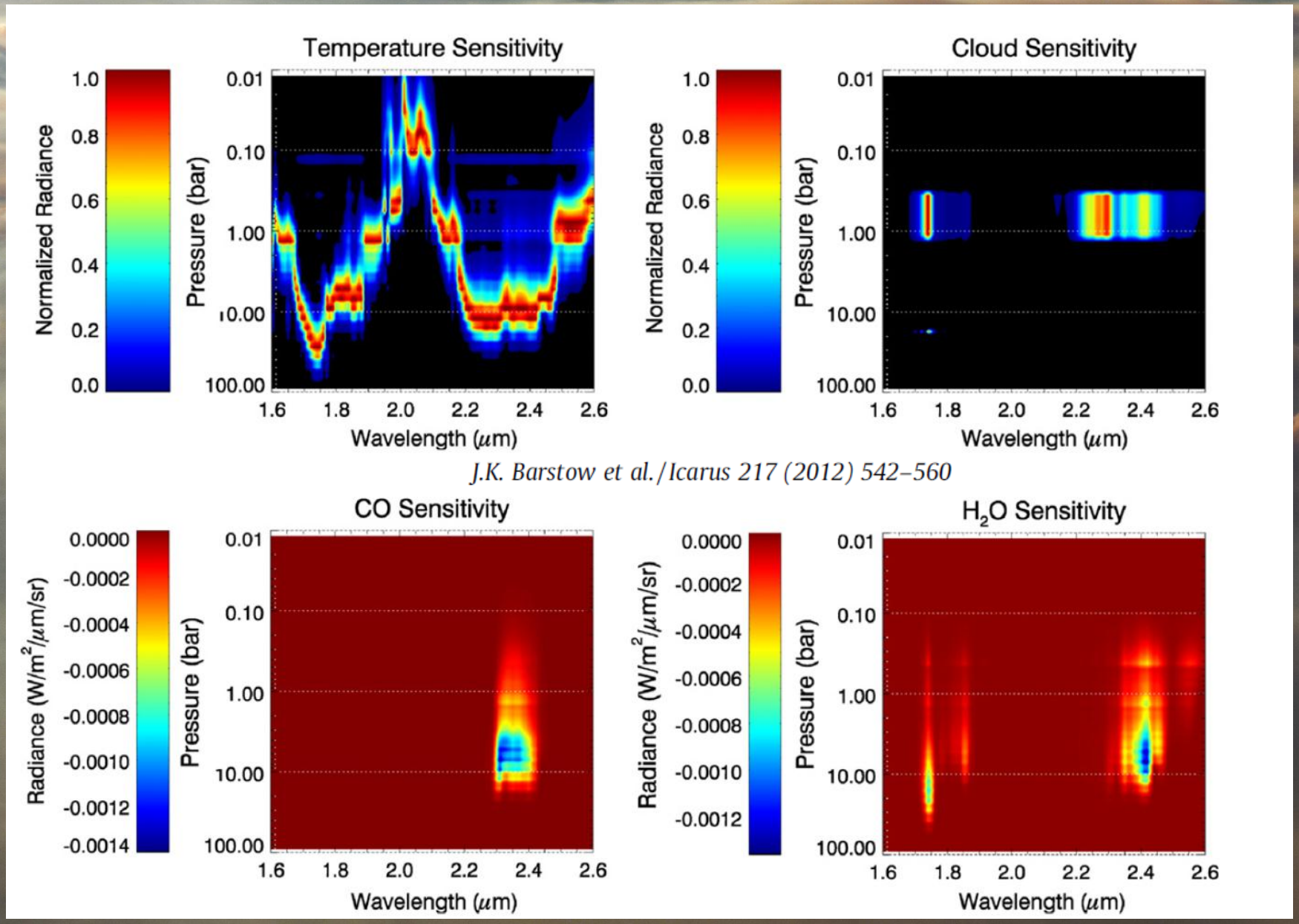
Knollenberg and Hunten, 1979

The most complete description of the vertical profile of the Venus clouds was obtained by the Pioneer Venus Large Probe Cloud Spectrometer.

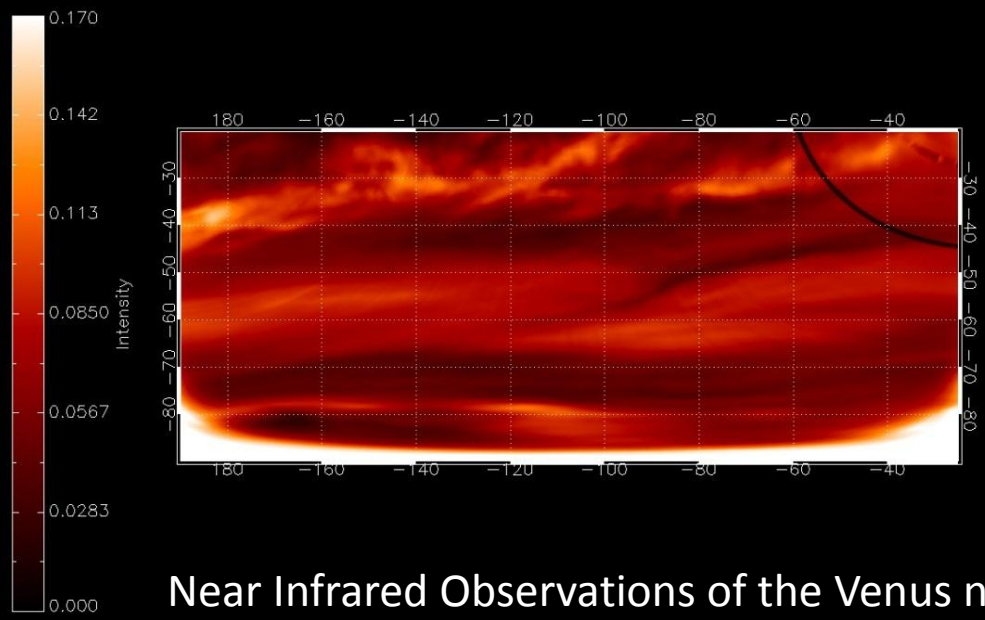
Peering Into the Clouds at Near Infrared Wavelengths



Near Infrared Observations of the Night Side



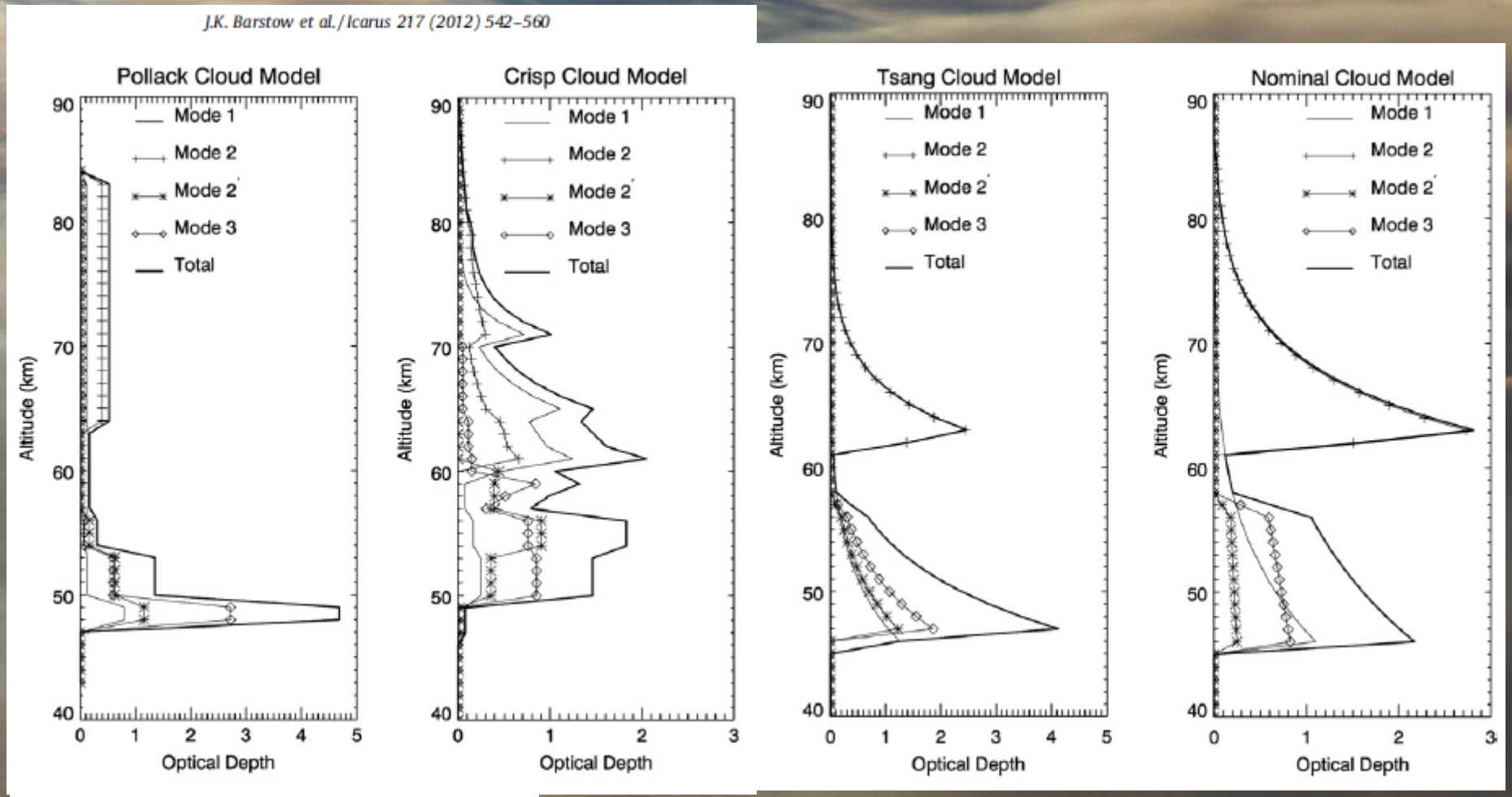
Spatial Variations in the Middle and Lower Clouds



Bailey et al. 2008

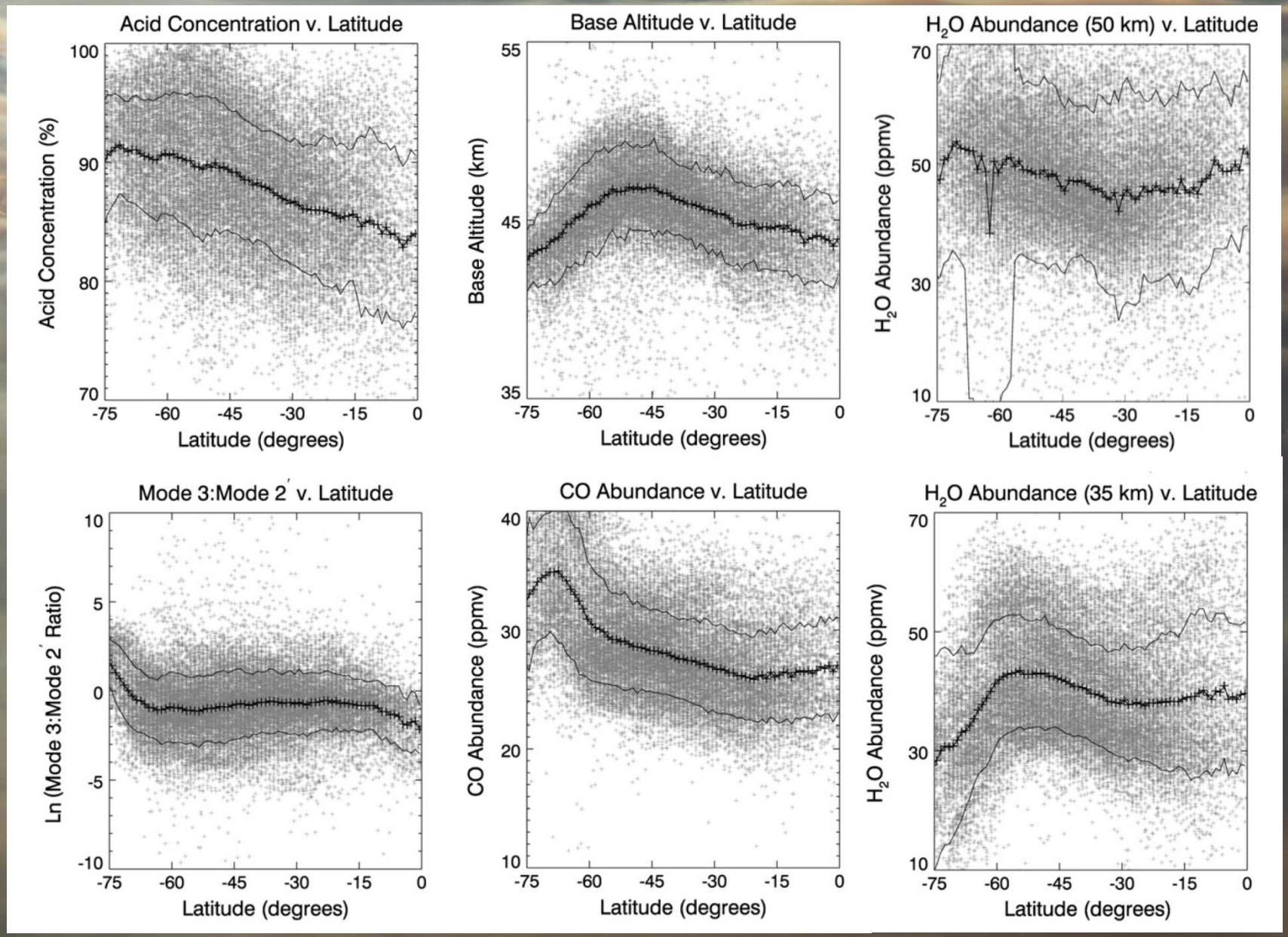
Near Infrared Observations of the Venus night side show substantial variability in the middle and lower cloud decks.

Cloud Optical Depth



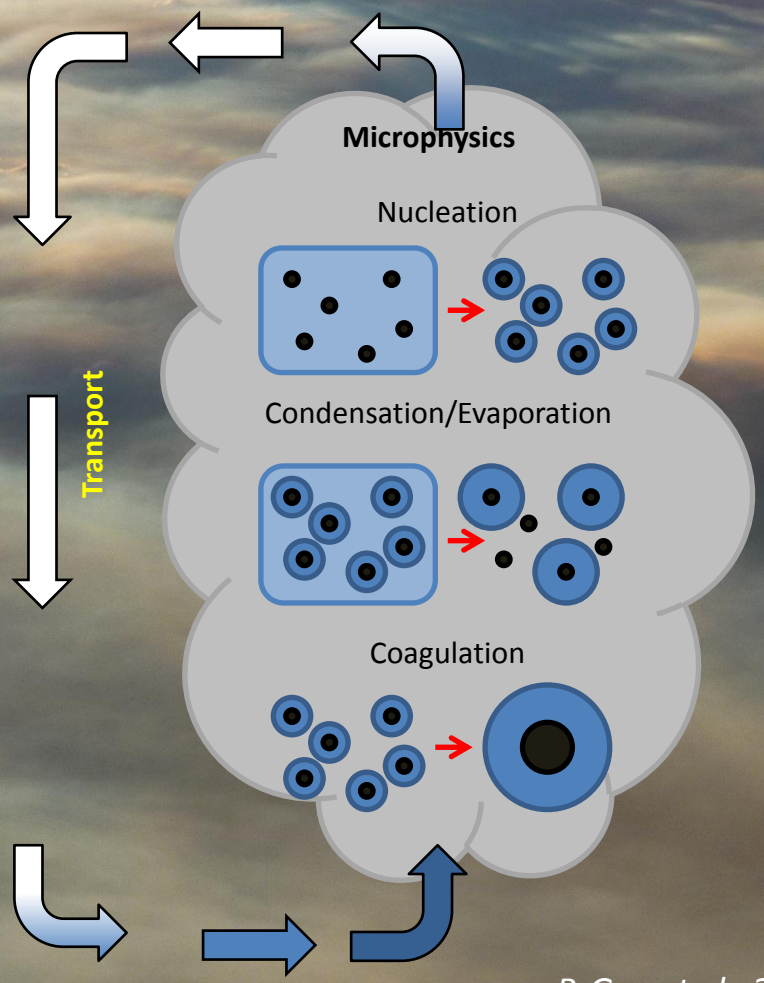
J.K. Barstow et al. / Icarus 217 (2012) 542–560

Cloud Properties and Trace Gases



J.K. Barstow et al./Icarus 217 (2012) 542–560

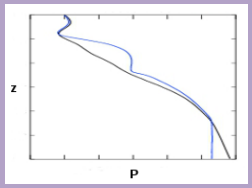
Modeling the Venus Clouds



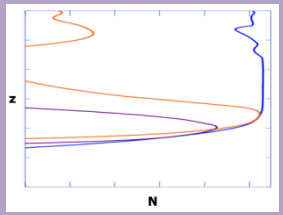
P. Gao et al. 2012

Concentrations & Distributions

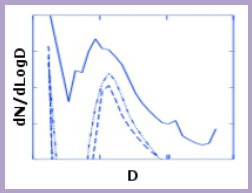
Gas-Altitude Distribution



Particle-Altitude Distribution



Particle-Size Distribution



Sophisticated cloud models are yielding new insights into the processes that produce and maintain observed cloud structure.

Composition/Chemistry/Aerosols

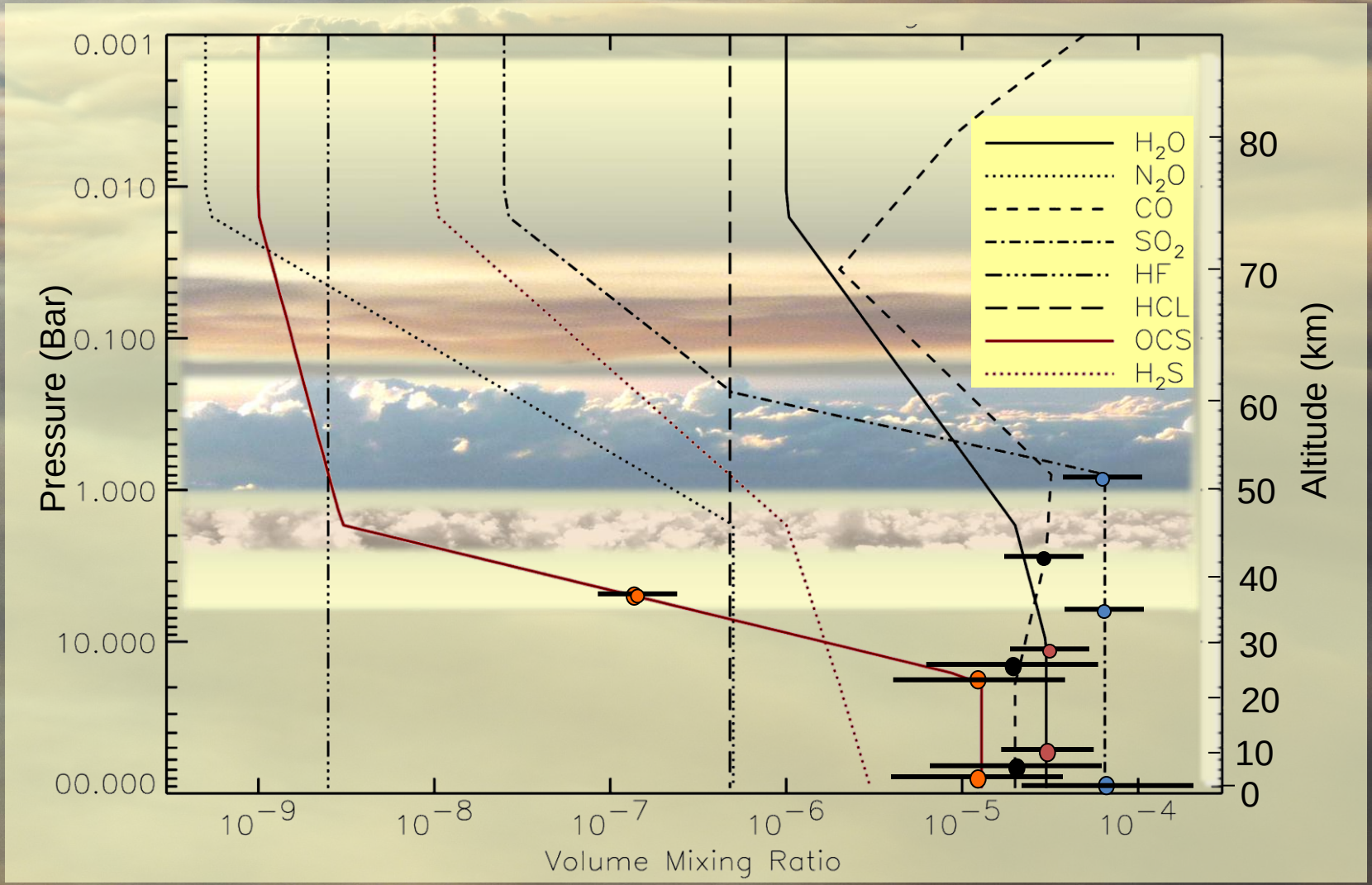
- Major Constituents:
  - CO_2 (~96.4%) N_2 (~3.5%)
- Major Trace Gases:
  - SO_2, OCS, H_2S, H_2O, CO, H_2SO_4
- Reactive Gases:
  - HCl, HF, HBr, H_2, SO_3, OH
- Mysteries
  - O_2

Summary of Major Trace Gases

De Bergh et al. PSS, 2006

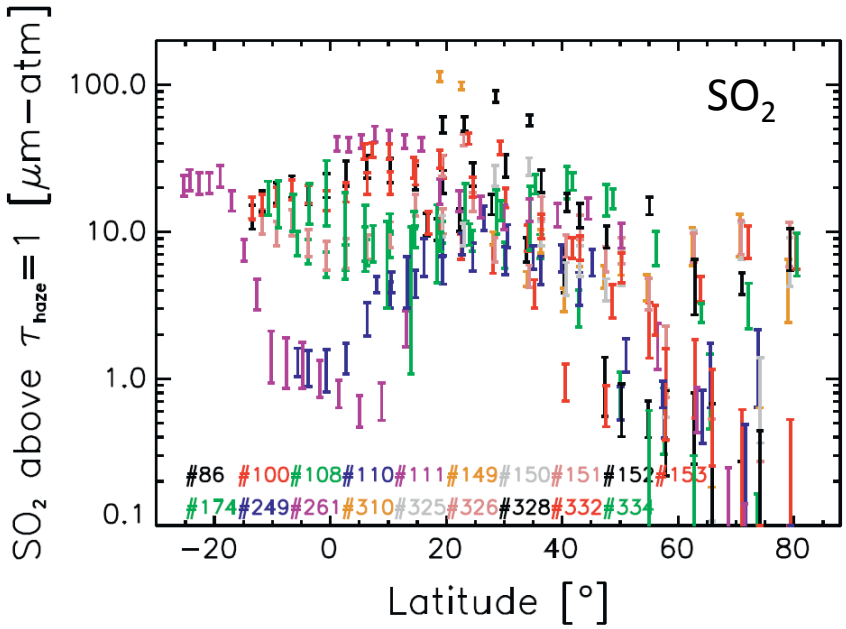
Gas	Altitude range (km)	Mixing ratio (ppm)	Comment	Note	Reference
CO	30	23 ± 7		(a)	Pollack et al. (1993), Taylor et al. (1997)
	40	29 ± 7		(a)	Pollack et al. (1993), Taylor et al. (1997)
			[1]	(b)	Collard et al. (1993), Marcq et al. (2005)
HCl	15–30	0.5 ± 0.15		(a)	Bézard et al. (1990), Pollack et al. (1993)
HF	30–40	0.005 ± 0.002		(a)	Bézard et al. (1990), Taylor et al. (1997)
H_2O	5–60	30 ± 10		(c)	Ignatiev et al. (1997) (model B)
	10–20	20 ± 10		(c)	Ignatiev et al. (1997) (model A)
	10–26	28^{+18}_{-5}		(d)	Donahue et al. (1992, 1993, 1997)
	10–40	30^{+15}_{-10}		(a)	Pollack et al. (1993), de Bergh et al. (1995)
					Meadows and Crisp (1996)
					Taylor et al. (1997)
				(b)	Drossart et al. (1993)
	51	6^{+4}_{-3}		(d)	Donahue et al. (1992, 1993, 1997)
	55	4^{+3}_{-2}		(d)	Donahue et al. (1992, 1993, 1997)
	55–65	5–15	[1][5]	(e)	Ignatiev et al. (1999), Koukouli et al. (2005)
		6–100	[5]	(j)	Schofield et al. (1982), Koukouli et al. (2005)
	65–100	0.05–5.5	[3]	(f)	Encrenaz et al. (1991, 1995)
					Sandor and Clancy (2005)
SO_2	12	22 ± 3		(g)	Bertaux et al. (1996)
	22	38		(g)	Bertaux et al. (1996)
	42	130		(g)	Bertaux et al. (1996)
	52	110		(g)	Bertaux et al. (1996)
	35–45	130 ± 40		(a)	Bézard et al. (1993)
	69	0.01–0.5	[1][2][3]	(e)	Zasova et al. (1993)
	69	0.02–0.6	[1][2][3]	(h)	Na et al. (1994)
SO	69	0.012 ± 0.005	[3]	(h)	Na et al. (1994)
OCS	30	14 ± 6		(a)	Pollack et al. (1993), Taylor et al. (1997)
	38	0.35 ± 0.1		(a)	Pollack et al. (1993), Taylor et al. (1997)
H_2SO_4	35–50	0.1–10	[1][4]	(i) (f)	Kolodner and Steffes (1998), Jenkins et al. (2002)

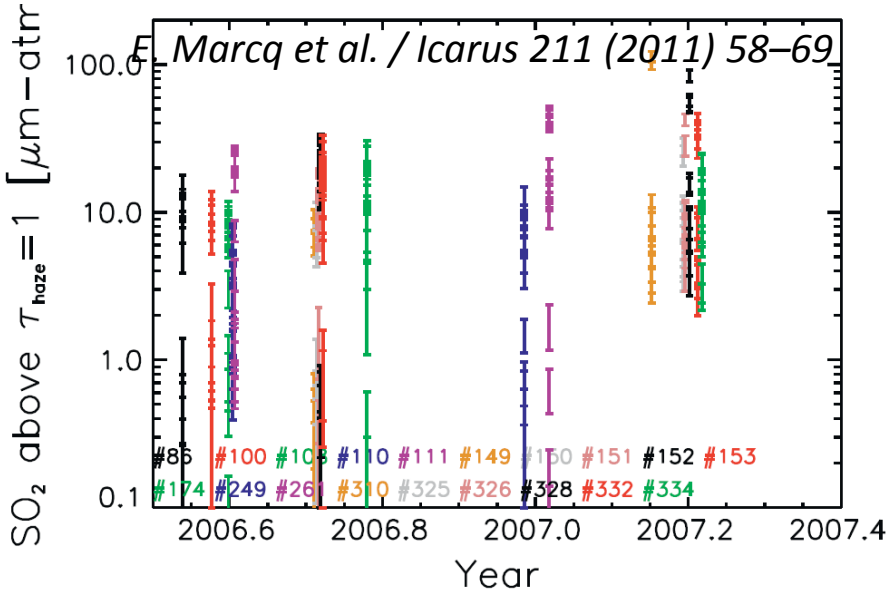
Trace Gas Profiles from Near IR Observations



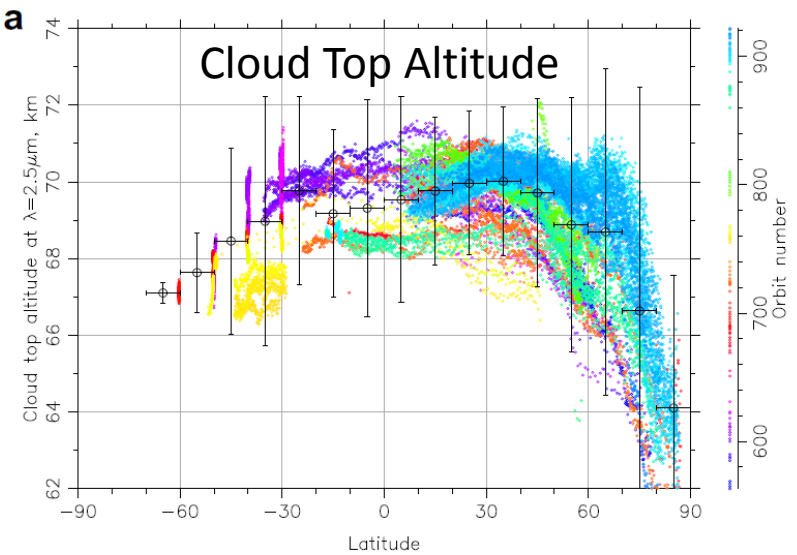
- Trace gases (principally SO_2, H_2O, CO, and OCS) reinforce the greenhouse provide opacity between the strong CO2 absorption bands.
- There are still large uncertainties in the trace gas mixing ratios below the clouds

SO_2 and H_2O Variability Above the Cloud Tops

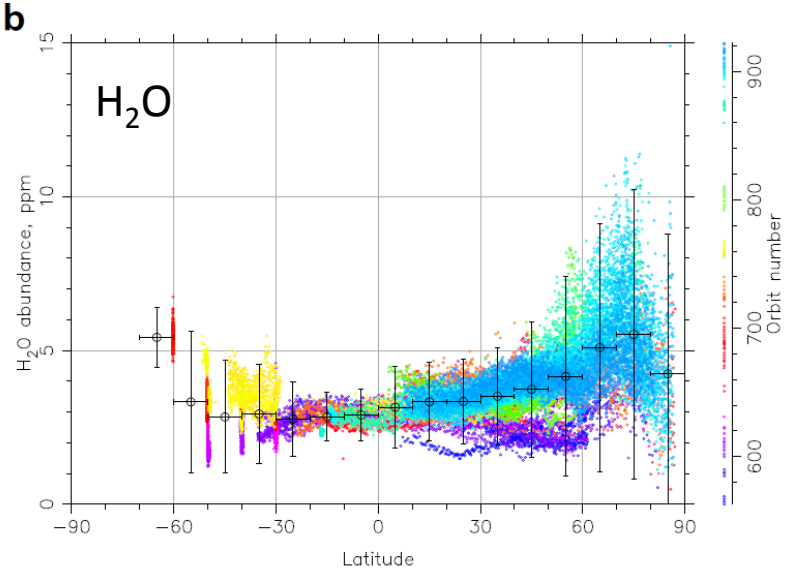




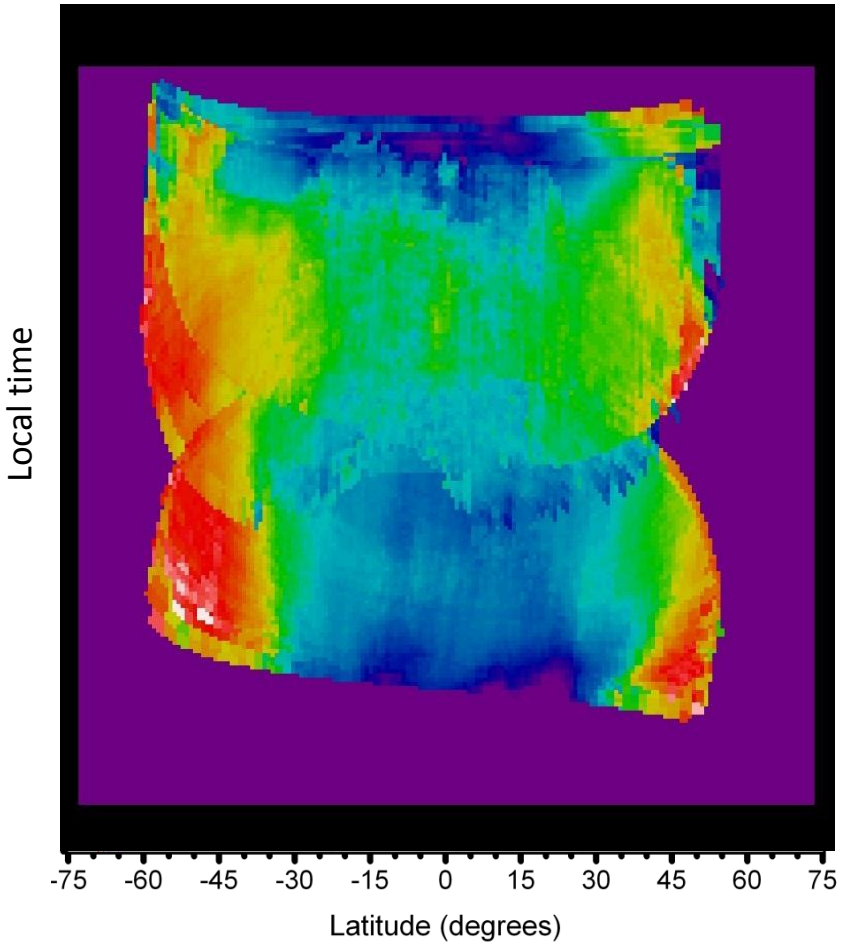
E. Marcq et al. / Icarus 211 (2011) 58–69

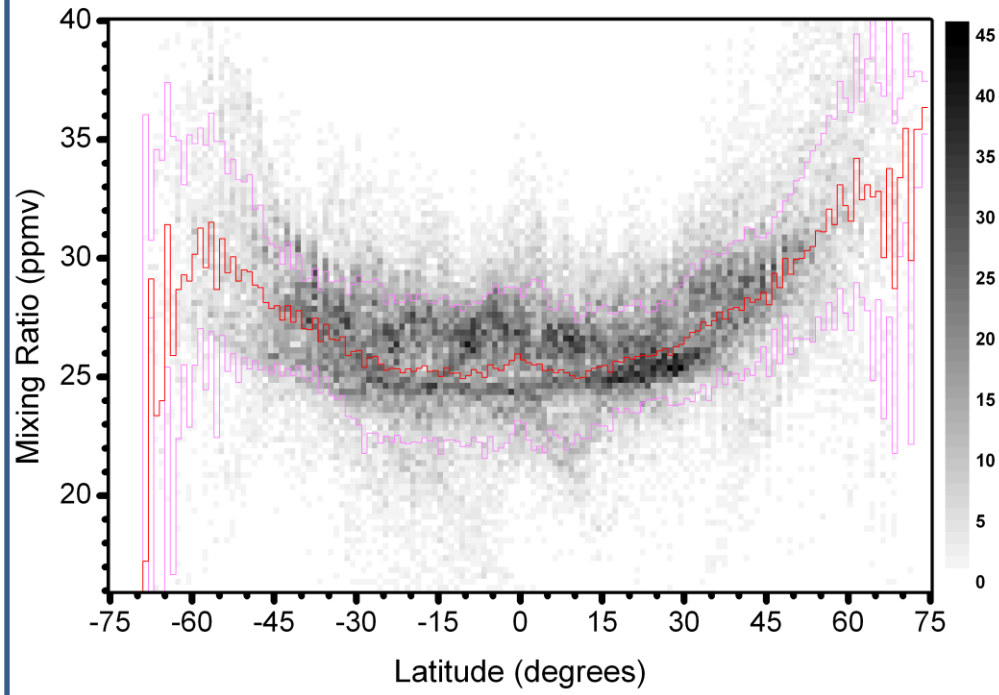


V. Cottini et al. / Icarus (2011)



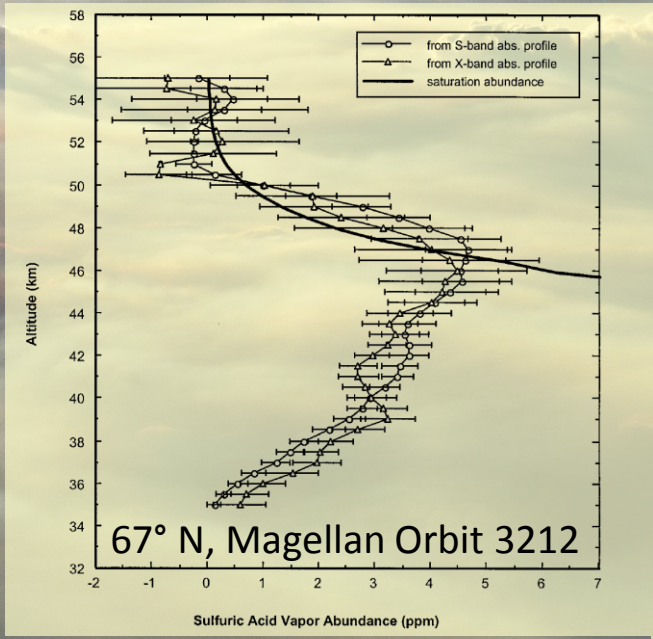
Sub-Cloud Carbon Monoxide Distribution

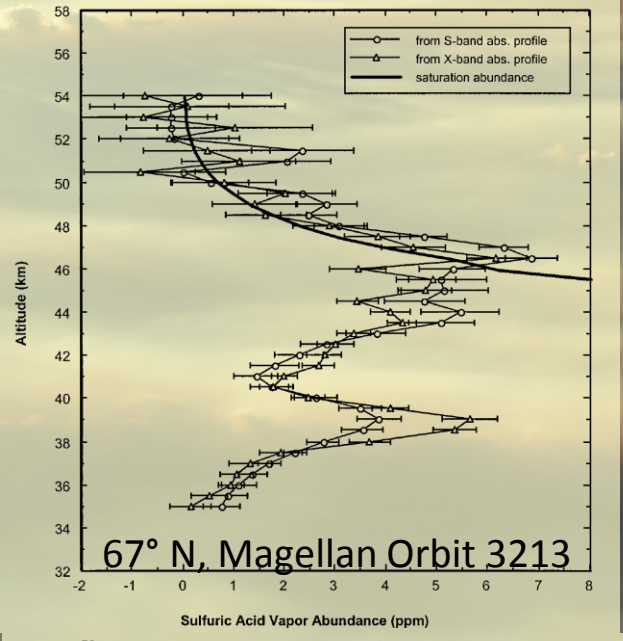




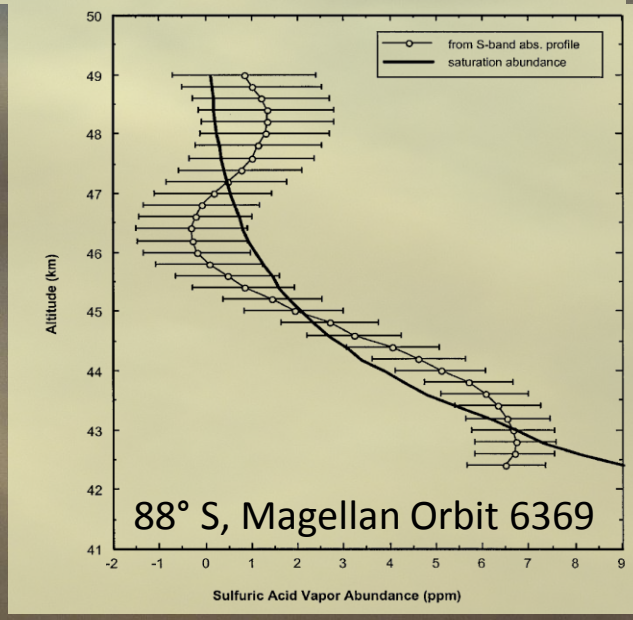
Near infrared observations of the night side have been analyzed to describe spatial variations in the CO abundance just below the cloud base (~36 km, Cotton et al. 2011).

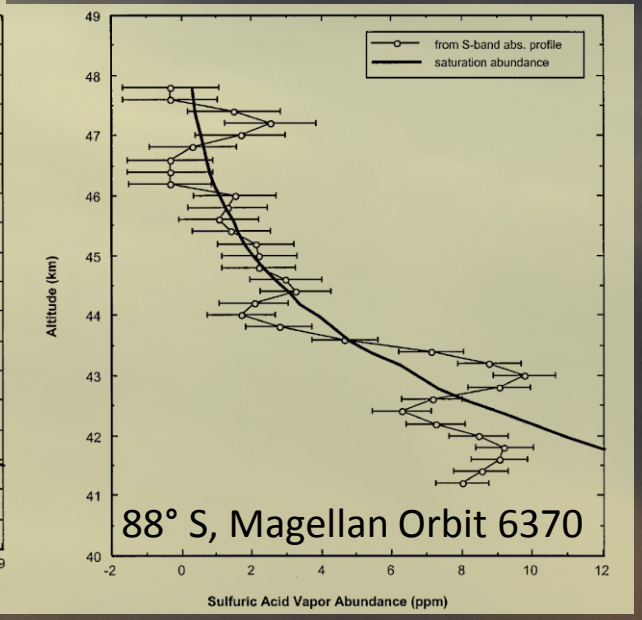
Spatial and Temporal Variations in H_2SO_4 Vapor





Magellan radio occultation measurements show substantial spatial and temporal variations in the H_2SO_4 vapor concentration near the cloud base

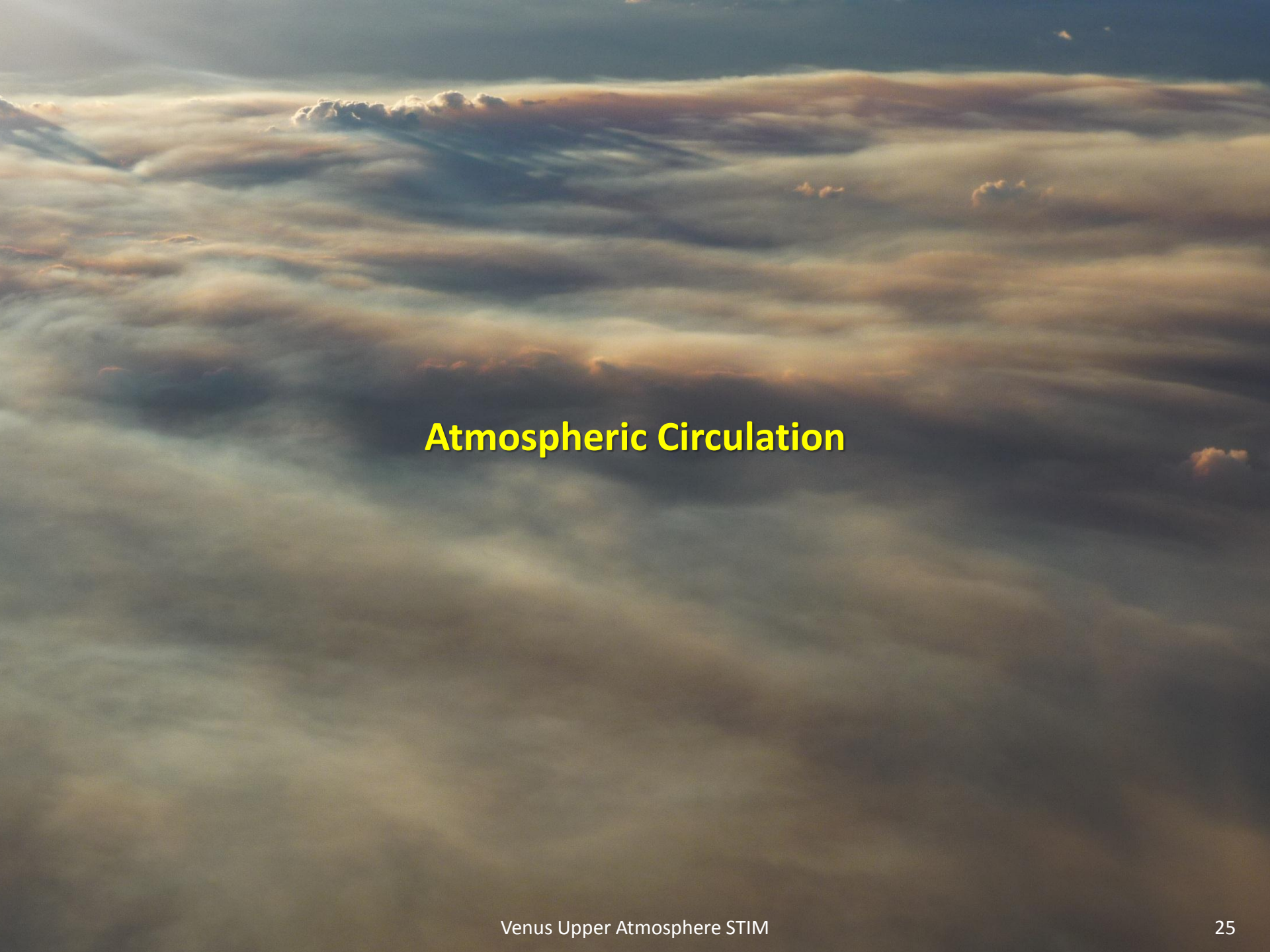




Questions:

- Are these H_2SO_4 variations associated with the observed variations in the middle and lower cloud densities?
- Does it rain on Venus?

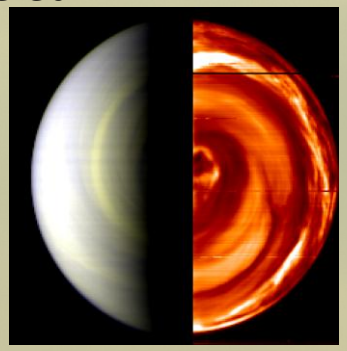
KOLODNER AND STEFFES (1998)



Atmospheric Circulation

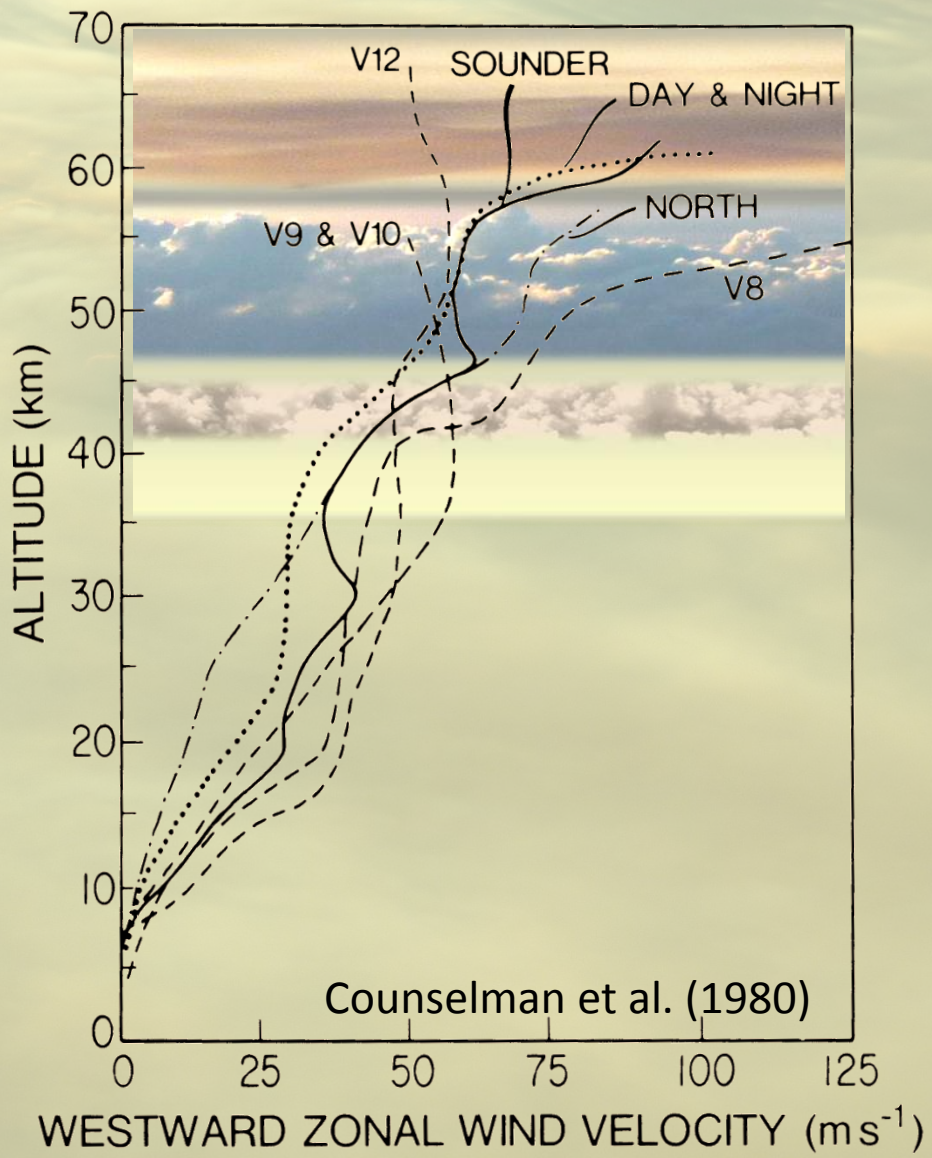
The Large Scale Circulation

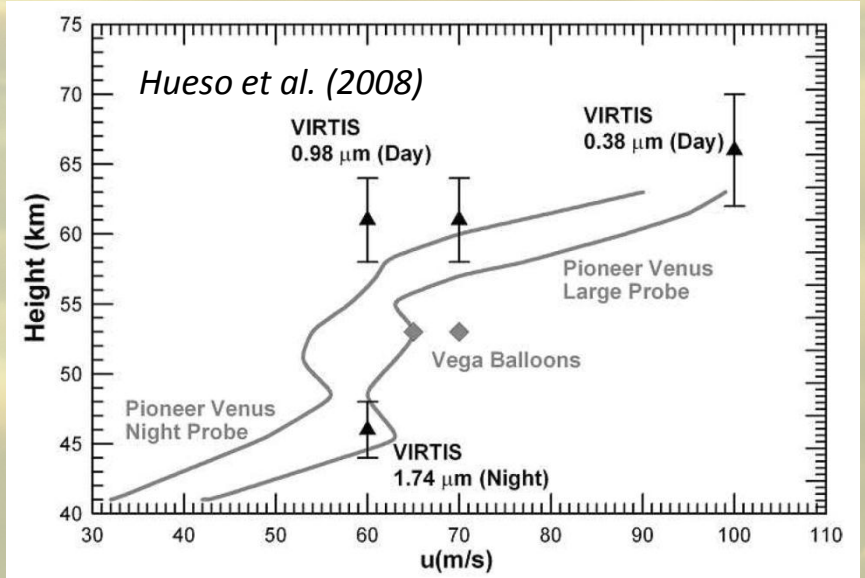
- The most prominent and perplexing feature of the Venus general circulation is a global atmospheric super-rotation
  - Persistently “retrograde” (East to west) at all levels of the atmosphere between the surface and the mesopause
    - Appears to be in “cyclostrophic balance” with the temperature field at these levels
  - Largest wind velocities are seen at the cloud tops, where the entire atmosphere appears to rotate with a ~4-day period, almost 60 times as fast as the solid surface.
- The mechanisms responsible for maintaining the superrotation have remained elusive since its existence was confirmed in the late 1960’s
  - Appears to be associated with the atmospheric thermal tides, as first proposed by Fels and Lindsen (1974), but the details of the wave-mean flow interactions have not yet been convincingly measured or modeled.

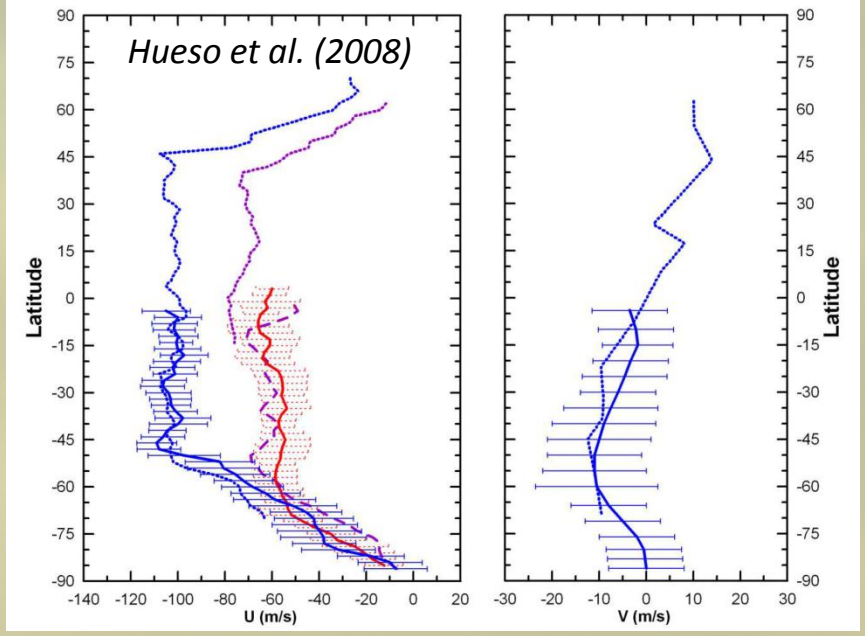


- Other features of the large scale circulation include:
  - Polar vortices in both hemispheres
  - A direct “Hadley” circulation in the lower atmosphere
  - A thermodynamically-indirect circulation in the mesphere

The Venus Superrotation







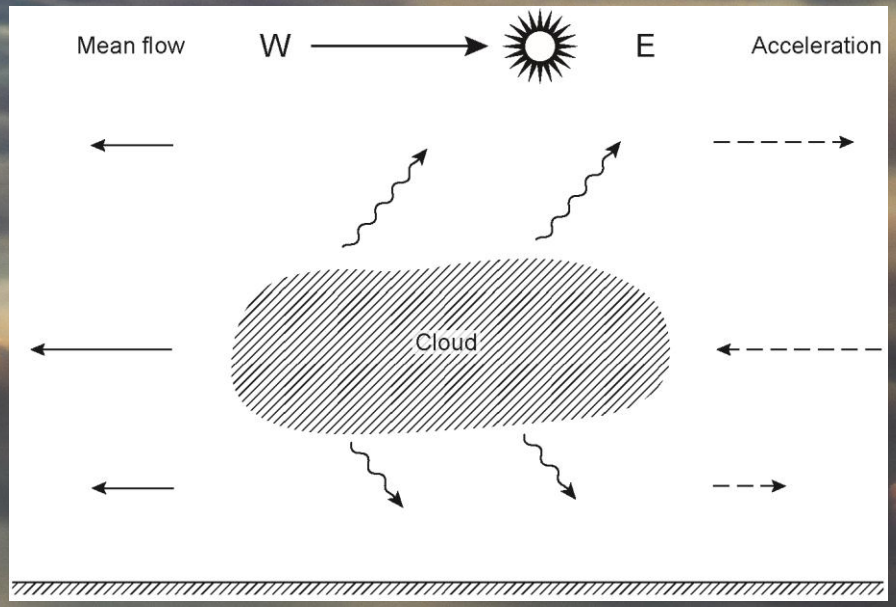
Theoretical Mechanisms of Superrotation

From :Curt Covey, Venus Dynamics Workshop 2007

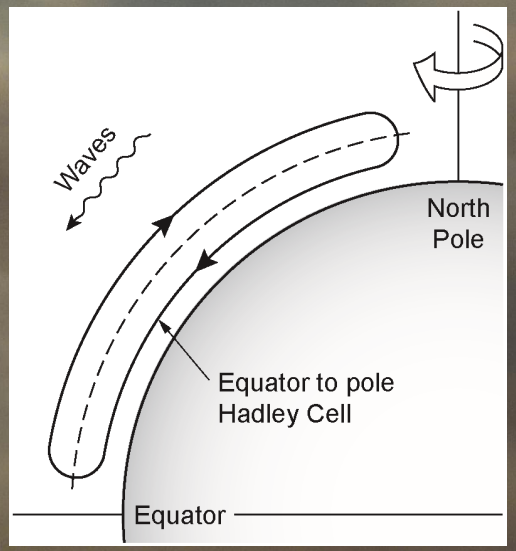
- **Involving day / night cycle (Schubert and Whitehead 1969, Fels and Lindzen 1974, . . . Takagi and Matsuda 2007)**

i.e. atmospheric tides:

"Momentum is deposited [opposing superrotation] where waves are absorbed, and a reaction force [accelerating superrotation] is produced where waves are generated." -- Gierasch 1997



- **Not involving day / night cycle (most notably Gierasch 1973, Rossow and Williams 1979):**
  - **Zonal mean flow (Hadley cell) transports momentum from solid planet upward -- and poleward.**
  - **Waves (from barotropic instability?) transport angular momentum equatorward.**



The biggest problem with GRW is retaining angular momentum at low latitudes.

Early History of Venus GCMs

From :Curt Covey, Venus Dynamics Workshop 2007

Ancient History: up to Eugenia Kalnay de Rivas (1973, 1975)

- No superrotation, by assumption or by calculation

Middle Ages: Richard Young & James Pollack (1977)

- Good news:
  - Superrotation at model top for all latitudes
  - Plausible mechanism: weak GRW amplified by instability
  - 4-Earth-day planetary waves resembling cloud-top UV features
- Bad news:
  - Extremely lo-res by today's standards: 4 wavenumbers, 16 levels
  - Vertical sub-gridscale diffusion doesn't conserve momentum
  - No superrotation below 30 km altitude

Renaissance: Tony Del Genio et al. (1990s)

- Slowly-rotating all-land Earth GCM
- Hydrology, day / night and seasonal cycles all removed
- Thick planetwide clouds assumed at 150 and 550 mbar levels
- Superrotation via GRW at and below cloud tops (as observed) if:
  - Higher levels nearly decoupled from lower levels (via assumed clouds)
  - New computer, double-precision arithmetic (momentum conservation)

  $\Rightarrow$ "weakly forced / weakly dissipated system"

Recent History of Venus GCMs

From :Curt Covey, Venus Dynamics Workshop 2007

Yamamoto and Takahashi (2003-): CCSR / NIES Model

- Variant of Center for Climate System Research's Earth GCM
- Prescribed solar heating in atmosphere; prescribed surface temperature
- Superrotation via GRW mechanism **if** solar heating is "larger than that in the real atmosphere below 55 km" and / or gradient of surface temperature is "used as a tunable parameter" to boost Hadley circulation

Lee et al. (2005-2006): Hadley Centre / Oxford Simplified Venus Model

- Variant of UK Meteorological Office's Earth GCM
- More realistic solar heating → less realistic (slower) superrotation

Herrnstein and Dowling (2006): Venus EPIC Model

- Variant of Explict Planetary Isentropic Coordinate outer-planets GCM
- Including topography → even slower superrotation

Lebonnois et al. (2006-): LMD Venus GCM

- Variant of Laboratoire de Meteorologie Dynamique's Earth GCM
- Focus on radiative transfer

Lee et al. (2006-): Venus WRF

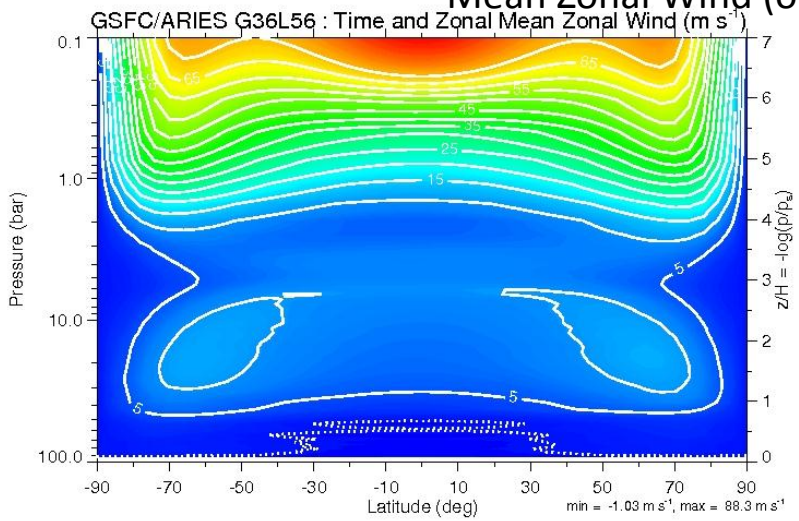
- "Global planetary" variant Weather Research and Forecasting GCM

Recent History of Venus GCMs (continued)

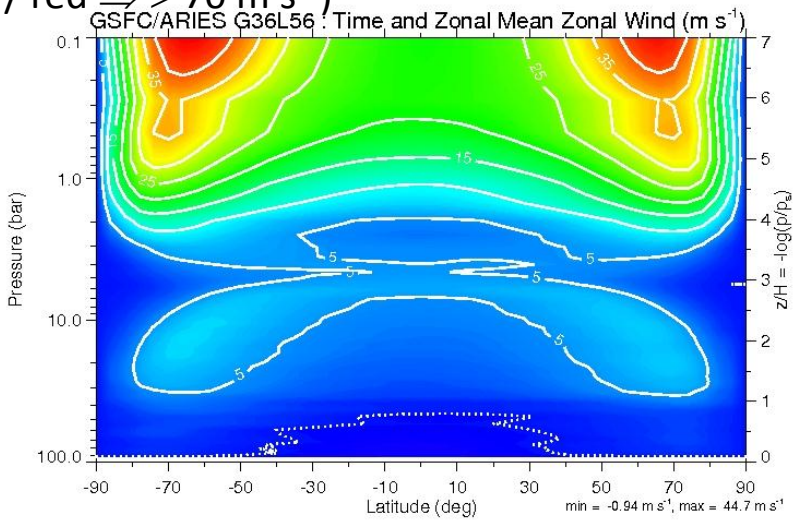
From :Curt Covey, Venus Dynamics Workshop 2007

- Hollingsworth et al. (2007) -- "Name your poison" for GRW mechanism:

  Mean Zonal Wind (orange / red $\Rightarrow$ > 70 m s^{-1})



The right superrotation with . . .
the wrong heating rate

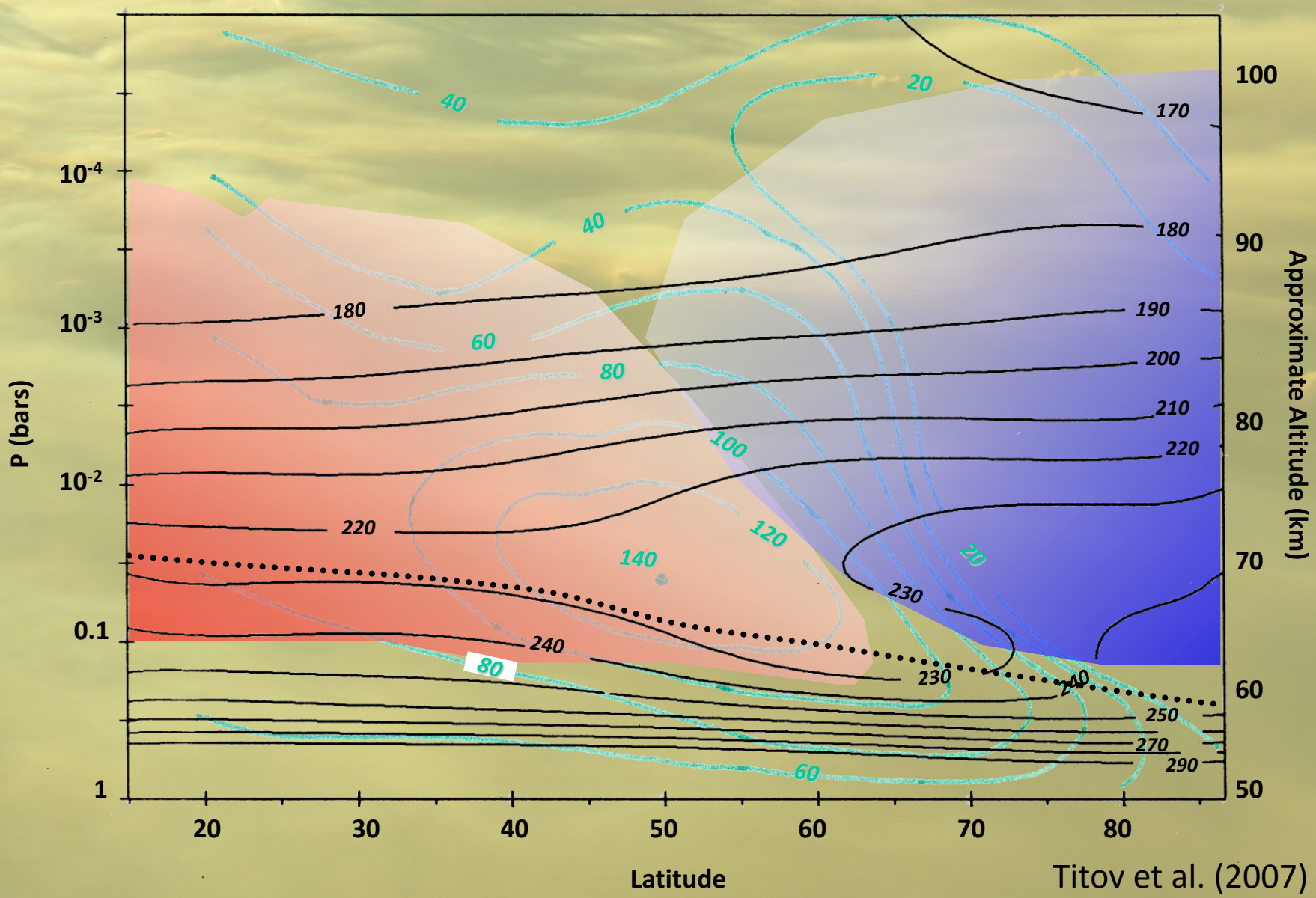


or the wrong superrotation
. . .with the right (PV) heating rate.

- Takagi and Matsuda (2007) -- Atmospheric tides can **initiate** as well as maintain superrotation:

  ". . . the downward propagaing semidiurnal tide . . . induces the mean zonal flow opposite to the Venus rotation in the lowest layer adjacent to the ground. Surface friction acting on this counter flow provides the atmosphere with the net angular momentum from the solid part of Venus."

Mesospheric Temperature and Wind Fields



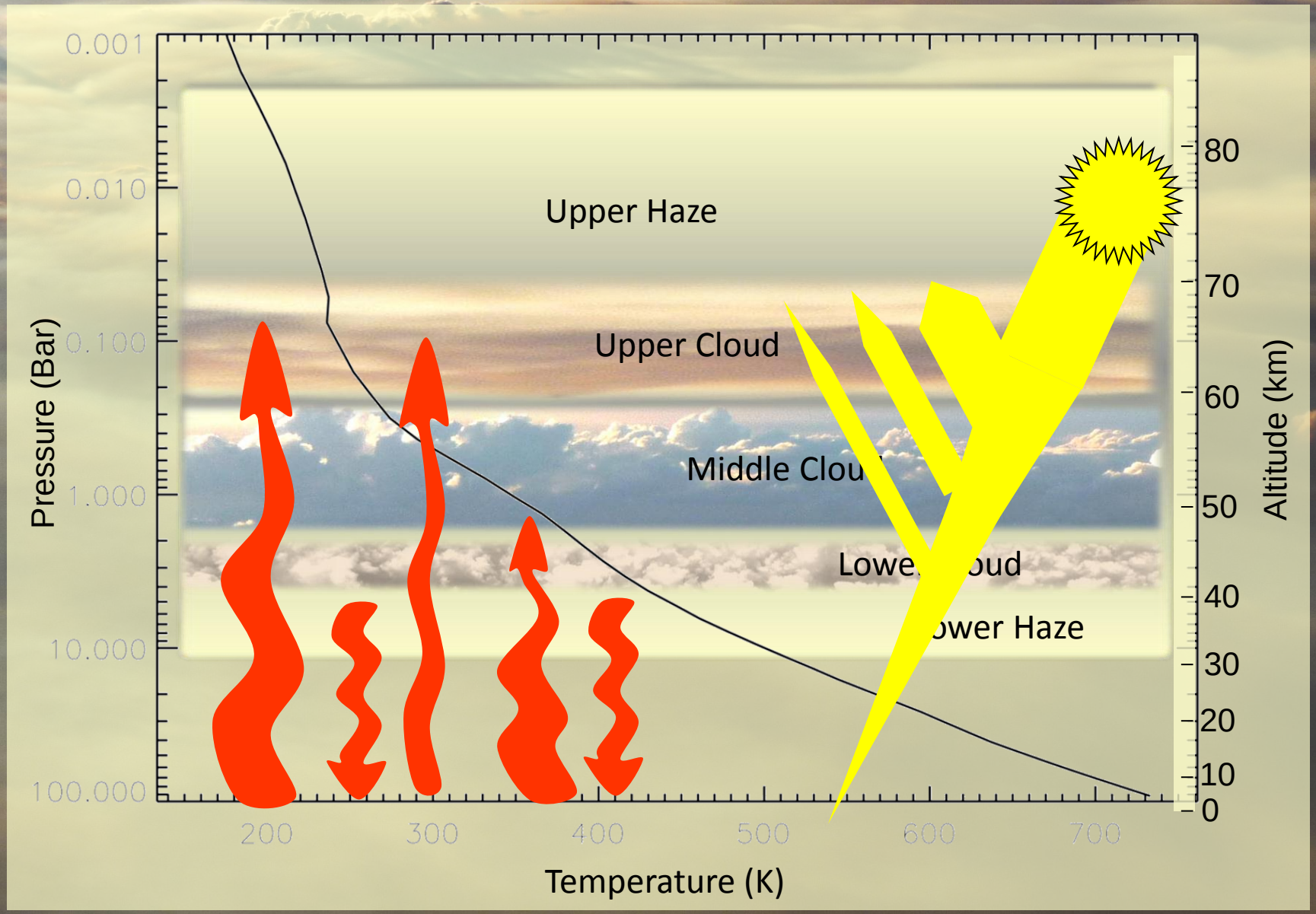
Titov et al. (2007)

The Next Steps for Venus GCM's

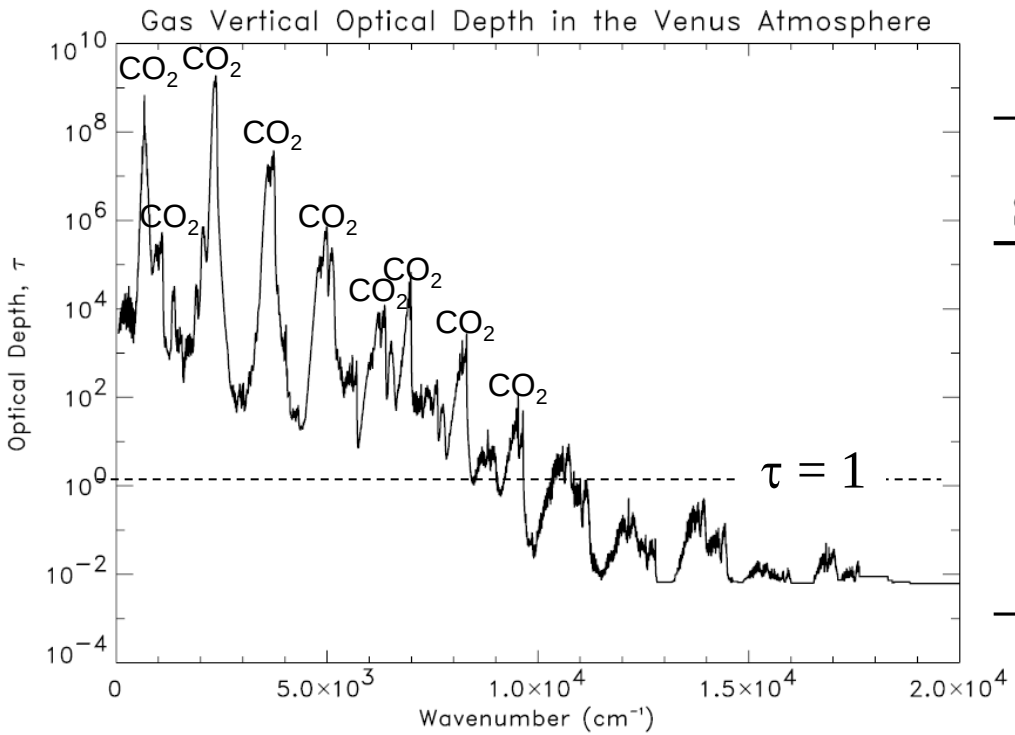
"To better constrain and help improve the GCMs, a crucial point is to be able to correctly reproduce the thermal environment in the 45-100 km region at any latitude. That means we need to know this temperature field (more and more data available from Virtis and VeRa), but also the opacity sources (particle distributions) and the radiative fluxes in solar radiation and in thermal emissions. Constraining the distribution of opacity sources is a key point to get the fluxes (and the temperatures) right in the GCMs. PFS is seriously missing, here."

Sebastien Lebonnois , 24 January 2013

The Venus Greenhouse



Gas Absorption in the Venus Atmosphere



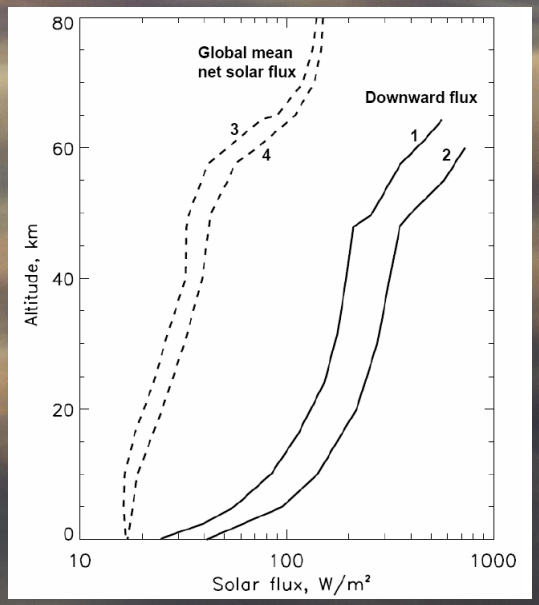
Source Deleted	Change in Surface Temperature, K
CO_2	-420
Clouds	-140
H_2O	-70
OCS	-12
CO	-3
SO_2	-3
HCl	-2

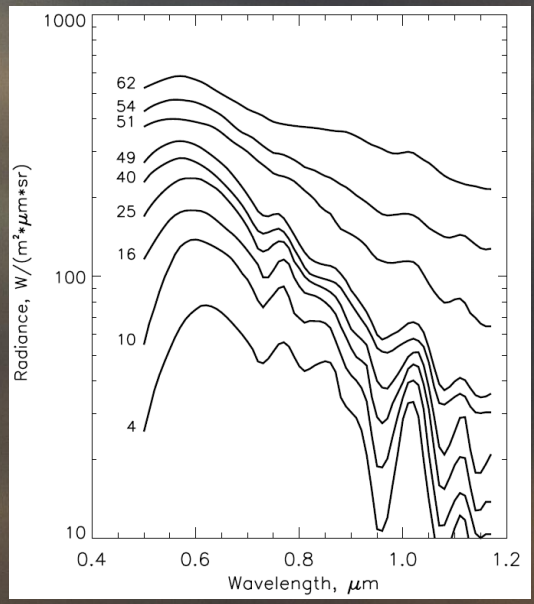
Titov et al. (2007)

- CO_2 and other absorbing gases (SO_2, H_2O, CO) largely preclude emission from the surface of Venus throughout the infrared
- Even Rayliegh scattering is a significant source of extinction within the lower atmosphere, below the cloud base

Venus Greenhouse Effect

- Although Venus receives almost twice as much solar radiation as Earth
  - Its clouds reflect ~76% of the incident radiation
  - Total available radiation is ~170 W/m^2
- About half of the absorbed solar flux is deposited within or above the cloud tops (~65 km)
  - Visible absorption by the unknown UV absorber,
  - Near IR absorption by the H_2SO_4 clouds and CO_2
- Only ~2.6% of the solar flux incident at the top of the atmosphere reaches the surface
  - Solar flux at the surface is ~17 W/m^2 (global avg.)
- Surface temperature of ~730 K maintained by an efficient atmospheric greenhouse mechanism
  - Net downward thermal flux at surface ~15,000 W/m^2
  - There are no true atmospheric windows at IR wavelengths > 3 μm

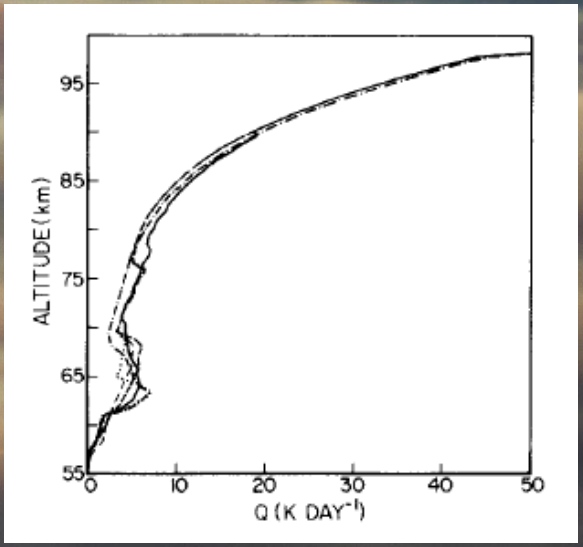




Solar heating of the Cloud Tops

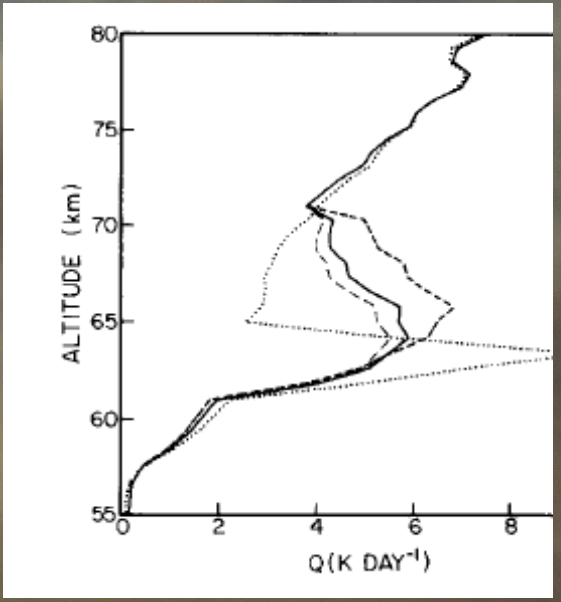
Because most of the solar energy is deposited within the upper cloud, the heating rates within the upper cloud are sensitive to:

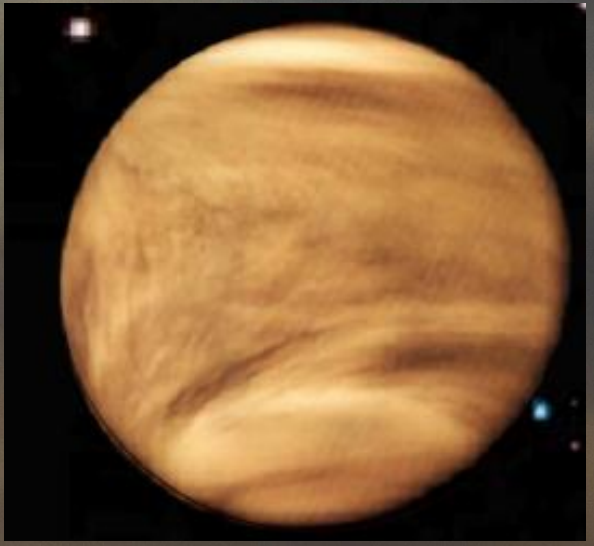
- **Variations in the vertical structure of the cloud tops**
- **The vertical distribution of the unknown UV absorber within the upper cloud**



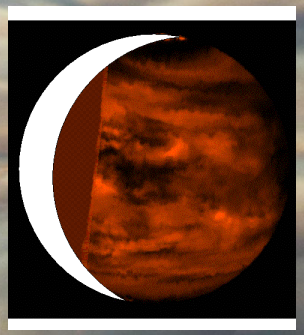
Sensitivity of solar heating rates to cloud top structure

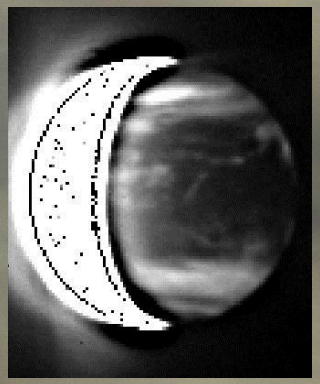
The solar heating within the upper cloud is strongly influenced by the amount and distribution of the UV absorber.

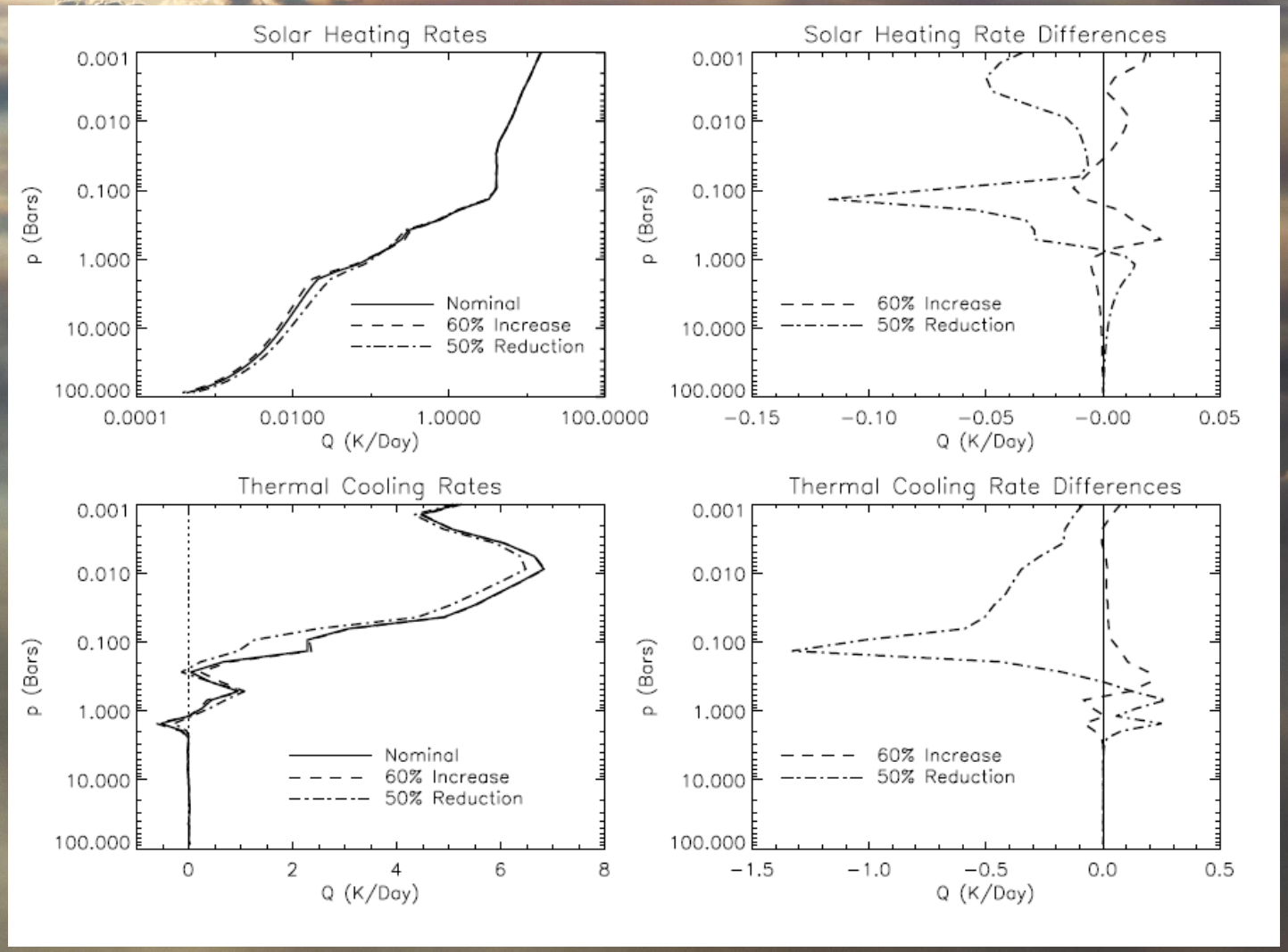




Impact of Spatial Variations in the Clouds



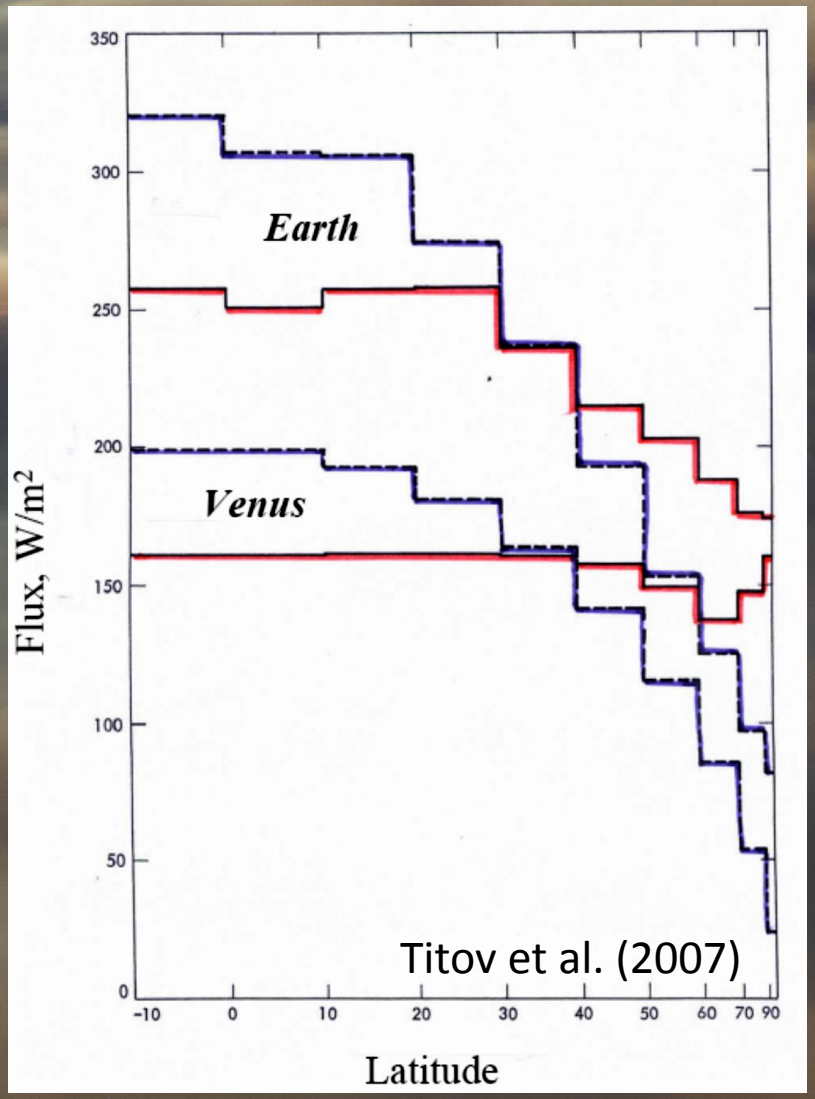




Spatial variations in the Middle and Lower Clouds associated with the Near-IR features produce larger variations in the thermal cooling than in the solar heating rates.

Latitude Distribution of Reflected solar and Emitted Thermal Flux

- There are large differences in the latitude distribution of the reflected solar and emitted thermal fluxes from Earth and Venus
- The reflected solar flux decreases strongly with latitude on both planets
  - Somewhat more strongly for Earth
    - High albedo polar caps
    - Increased reflectance from oceans
- For Venus, there is little latitude variation in thermal emission from the nearly isothermal cloud tops
  - Dynamical processes transport more heat from the equator to the poles



Conclusions

- Existing ground-based, orbiter and entry probe measurements have provided substantial insight into some aspects of the atmospheric
  - Thermal structure
  - Composition and cloud distribution
  - Atmospheric motions
  - Greenhouse forcing of the thermal structure

- While these observations have provided intriguing clues into several aspects of the Venus environment, in many cases they have raised as many questions as they have answered
  - What is the UV absorber
  - What process maintains the cloud structure
  - What processes drive the atmospheric superrotation
  - and many more ….

- New observations from well-equipped entry probes and long-lived orbiters are needed to address these questions.