Venus Atmosphere Dynamics: A Continuing Enigma

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1 INTRODUCTION AND FOCUSED LITERATURE REVIEW

The dynamics of the Venus atmosphere presents a major unsolved problem in planetary science: the so-called superrotation of the lower atmosphere and its transition to a subsolar-to-antisolar circulation in the upper atmosphere. (In this paper we place the dividing line between the lower and upper atmosphere at 90–100 km altitude (pressure 0.39 to 0.028 mbar), the base of the day-side thermosphere.) Sup errotation has also been observed in the atmosphere of Titan, the only other slowly rotating world with a substantial atmosphere known at present; in this case also the transition to a different circulation in the upper atmosphere is also apparent but not well understood. Thus, the issues discussed below may be generic to any slowly rotating terrestrial planet's atmosphere.

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1.1 Lower Atmosphere

The lower atmosphere of Venus is observed to rotate in the same retrograde (westward) direction as the solid planet, to first approximation at constant angular velocity at any given altitude. The maximum superrotation rate, at cloud-top levels, is about once every 4 Earth-days, 60 times faster than that of Venus itself. This retrograde superrotating zonal (RSZ) flow has been known for over three decades, but at present there is still no adequate explanation. Not a single theoretical model using realistic formulations of the Venus atmosphere has been able to quantitatively reproduce this fundamental characteristic of the atmosphere of the nearest planet to Earth.

Whereas the RSZ circulation is not understood theoretically, the meridional (north-south) circulation of the lower atmosphere is even less well-known. A thermally direct Hadley cell (upwelling at the equator, poleward flow aloft, descending flow at high latitude, and equatorward flow at lower altitude) is expected at cloud levels where most of the solar energy absorption takes place in the Venus atmosphere. However, it has not been observed except for an indication of poleward motion in low-latitude cloud-tracked winds (*Schubert*, 1983). The latitudinal and vertical extent of such a circulation is unknown as well as whether two or more Hadley cells lie "stacked" above and below each other. Intriguing features of the polar circulation and thermal structure such as the polar vortex, polar dipole, cold collar, and reversed equator-pole temperature gradient (*Taylor et al.*, 1983) above the cloud tops are probably related to the Hadley cells.

The most recent comprehensive reviews of the thermal structure and dynamics of the Venus lower atmosphere have been presented by *Crisp and Titov* (1997) and *Gierasch et al.* (1997), respectively. A number of studies (*Fels and Lindzen,* 1974; *Pechman and Ingersoll* , 1984; *Fels* , 1986; *Leovy and Baker*, 1987; *Hou et al.*, 1990; *Newman and*

Leovy, 1992) indicate that momentum fluxes from thermal tides maintain super-rotation in the altitude range of 60–90 km (pressure ~ 0.21 bar to 0.39 mbar), at and above the level of Venus' planetwide cloud cover. The tides might act in combination with a direct equator-to-pole Hadley cell, which would transport retrograde momentum upward from the solid planet (*Gierasch*, 1975). However, if thermal tide amplitudes are small below the clouds (*Gierasch et al.*, 1997), then middle atmosphere dynamics could be decoupled from lower atmosphere dynamics. In that case, the key to unlocking the mechanisms generating superrotation would be contained in the deep atmosphere, especially in the lowest atmospheric scale height.

Two observed features of the superrotation illustrate why this should be the case. First, the RSZ winds are generally in the same direction all the way from the surface to well above the clouds (*Counselmann et al.*, 1980; *Gierasch et al.*, 1997). Second, as *Schubert* (1983) first pointed out, the product of atmospheric density times the mean zonal wind, i.e., the momentum per unit volume of the RSZ flow, is a maximum near 20 km altitude, well below cloud levels, but just above the lowest atmospheric scale height. The only plausible momentum source for producing a net zonal momentum in the atmosphere is the solid planet itself. Therefore, in attempting to understand superrotation, emphasis must be placed on the deep atmosphere, in particular the lowest scale height.

In this section we concentrate on developments in understanding the dynamics of the Venus lower atmosphere that have occurred since the publication of *Gierasch et al.* (1997). The reader is referred to that paper and references therein for extensive discussion of many of the fundamental aspects of Venus atmospheric dynamics. There have been few recent observational studies of significance for modeling the circulation of the atmosphere. This will change as two missions, Venus Express and Venus Climate Orbiter, both designed to make extensive remote sensing observations of the atmosphere of Venus, return data over the next several years.

Probably the most significant new developments regarding Venus lower atmosphere dynamics have occurred in theoretical models. *Young and Pollack* (1977) reported the first—and for many years the only—successful attempt to simulate RSZ with a three-dimensional general circulation model (GCM). This model included the atmosphere from the surface to the cloud tops, albeit at low resolution by today's standards (16 levels in the vertical dimension and wavenumber 4 in the horizontal). The model evolved cloud-top superrotation at all latitudes with maximum wind velocities of 30–85 m s^{-1} depending on initial conditions. The way the model did this seemed to involve a weak *Gierasch* (1975) mechanism (transport of retrograde zonal momentum upward at the equator and then poleward by a Hadley cell) amplified by *Thompson*'s (1970) suggested instability process. However, controversy arose about the model's vertical diffusion formulation, which may have exaggerated the RSZ flow (*Rossow et al.*, 1980; *Young and Pollack*, 1980), and in any case the model failed to produce any superrotation below 30 km altitude (~9.6 bar), where observations show that angular momentum per unit volume actually reaches its greatest value (*Schubert*, 1983).

Two decades later, *Del Genio et al.* (1993) and *Del Genio and Zhou*(1996) reported a series of simulations with Earth-like GCMs in which the assumed planetary rotation period was increased to that of either Titan (16 Earth days) or Venus (243 Earth days). These simulations retained the mass of Earth's atmosphere—about the same as Titan's but nearly two orders of magnitude less than Venus' atmospheric mass. Nevertheless, the results suggested ways the real Venus atmosphere could maintain the observed dynamical state. For Venus' planetary rotation rate, *Del Genio et al.* (1993) and *Del Genio and Zhou*(1996) obtained superrotation at virtually all latitudes and altitudes, provided that (1) higher levels of the atmosphere were decoupled from lower levels by a layer of high static stability and (2) care was taken to have the model conserve momentum to high accuracy. The first requirement seems to be satisfied by the actual Venus atmosphere (*Schubert*, 1983). The second requirement is understandable since, dynamically speaking, Venus' atmosphere is a weakly forced/weakly dissipative system, so a small numerical inaccuracy can ruin its simulation.

The simulations of *Del Genio et al.* (1993) and *Del Genio and Zhou*(1996) achieved superrotation by a strong *Gierasch* (1975) mechanism in which the requisite equatorward eddy momentum transport was accomplished by barotropic instability, as suggested originally by *Rossow and Williams* (1979). Similar results were obtained by *Hourdin et al.* (1992, 1995, 1996) and *Rannou et al.* (2006) in their Titan GCM simulations. The Gierasch mechanism emerged thereby as the favored explanation for Venus' superrotation. None of these simulations, however, was able to completely replicate the observed data. *Del Genio and Zhou*'s (1996) results, for example, fell an order of magnitude short of the real Venus in terms of cloud-top equatorial wind speed. These model simulations also assumed axisymmetric heating, thus excluding the day-night cycle and phenomena such as atmospheric tides and the "moving flame" (*Schubert and Whitehead*, 1969).

Yamamoto and Takahashi (2003a,b, 2004, 2006a) have taken the next logical steps of including the full mass of Venus' atmosphere and the day-night cycle in their GCM. They found that RSZ flow evolved by a strong Gierasch mechanism involving a single surface-to-cloud-top and equator-to-pole Hadley circulation, with a variety of waves transporting angular momentum equatorward. Unfortunately, it seemed necessary to alter the assumed thermal forcing of the atmosphere beyond the limits allowed by observation in order to establish a strong enough Hadley cell to make superrotation occur at the observed magnitude and extent—in short, to obtain the right answer for at least partly the wrong reason. Either a lower atmospheric heating rate orders of magnitude greater than observed (*Yamamoto and Takahashi*, 2003a,b), or an equator-to-pole surface temperature gradient far greater than expected to exist (*Yamamoto and Takahashi*, 2004, 2006a) appeared necessary for the model to "work."

Independent GCM simulations by ourselves (*Hollingsworth et al.*, 2007), *Lee* (2006), and *Lee et al.* (2006) are consistent with Yamamoto and Takahashi's experience. Our model, a full 3D global circulation model, is adapted from the NASA Goddard Space Flight Center ARIES/GEOS 'dynamical core' (*Suarez and Takacs*, 1995), which is based on the meteorological primitive equations. In contrast to a complex atmospheric general circulation model (AGCM), we utilize simplified forcing terms on the right sides of the governing equations, i.e., the net diabatic heating is expressed analytically, in addition to a Newtonian cooling term. Further, momentum drag is specified in terms of a Rayleigh friction, and a simple boundary layer scheme is imposed. Further details are provided in Hollingsworth et al. (2007). With unrealistically strong heating in the lower atmosphere, we found significant superrotation in our GCM simulations (Plate 1). RSZ flow occurred throughout the atmosphere except for very weak prograde flow at low altitudes and latitudes between $\pm 30°$, and maximum mean zonal westward winds of O(90 m s^{-1}) occurred at cloud-top levels, as observed. The bulk of the atmosphere below the clouds ($p > 1$ bar; $z/H \lesssim 5$) showed very weak north-south temperature contrasts and wind velocity of order (10 m s^{-1}). The zonal wind and temperature fields were associated with a deep, equatorially-symmetric mean meridional overturning (i.e., Hadley circulation) with rising motion at the equator, poleward motion aloft and sinking motion in high latitudes (see Figure 2 in *Hollingsworth et al.*, 2007). However, when lower atmospheric heating was consistent with Pioneer Venus observations (*Tomasko et al.*, 1980), we found only extremely weak O(1 m s^{-1}) superrotation in the upper tropical atmosphere; somewhat stronger winds O(10 m s^{-1}) were found in middle/high latitudes at high altitudes (Plate 2). Pole-to-equator temperature contrast, mean zonal flow, wave activity and associated equatorward eddy momentum transports—all prominent in the case of unrealistic heating—were dramatically reduced with realistic heating.

In agreement with our results, *Yamamoto and Takahashi* (2006a) state: "Although the superrotation is produced in the simplified AGCMs, a real Venusian superrotation mechanism is still unknown at the present stage. In addition to the further observations, the further improvements of AGCMs are needed in order to elucidate the real superrotation mechanism. Together with the improvement of the radiation code, more realistic surface processes should be incorporated into Venus atmosphere AGCM."

In assessing Venus lower atmosphere modeling efforts, some guidance may be obtained from current assessments of Earth climate models, which include both comparison of different models with different underlying assumptions (*Phillips et al.*, 2006) and a thorough exploration of "adjustable parameter space" (http://www.climateprediction.net). The stunning enhancement of computer capability since Venus GCMs were first developed certainly offers many opportunities along these lines. However, the question remains: What particular ingredient(s) are missing from Venus GCMs that prevent them from fully explaining superrotation?

The most recent version of Yamamoto and Takahashi's model, with day-night variations included, should be capable of simulating most of the superrotation mechanisms suggested since the phenomenon was observed, including the meridional circulation and non-axisymmetric eddies (*Gierasch*, 1975; *Rossow and Williams*, 1979), instability (*Thompson*, 1970) and diurnal solar heating variations such as thermal tides (*Schubert and Whitehead*, 1969; *Newman and Leovy*, 1992). A prominent exception is the class of theories involving surface-atmosphere interaction. Thermally excited gravity waves (*Fels and Lindze*n, 1974) originating near the surface might help to maintain superrotation (*Hou and Farrell*, 1987). Gravity waves, perhaps excited by the Venusian topography, were apparently detected by the Venera balloons (*Young et al.*, 1987). "One usually expects waves generated in the boundary layer to have small horizontal phase velocities and to contribute to drag rather than acceleration" (*Gierasch et al.*, 1997) and indeed the representation of so-called gravity wave drag is an important feature of modern Earth atmosphere GCMs, but these matters are only beginning to be explored in Venus lower atmosphere GCMs (Herrnstein and Dowling , 2007). Surface-atmosphere interaction is one of many issues that need to be addressed in order to simulate Venus' atmospheric circulation in a fully satisfactory manner.

[1] The tropopause (base of the mesophere) is conventionally placed at an altitude of 60±5 km, where the near-adiabatic lapse rate in the lowest levels of the atmosphere becomes less steep; the mesopause (base of the thermosphere) is at 90–100 km altitude.

1.2 Upper Atmosphere

The large-scale circulation of the upper atmosphere from ~90 to ~200 km altitude (upper mesosphere and thermosphere[1]) is a combination of two distinct flow patterns: (1) a relatively stable subsolar-to-antisolar (SS-AS) circulation cell driven by solar (EUV- UV) and IR heating, and (2) a highly variable retrograde superrotating zonal (RSZ) flow, in part a continuation of the lower-atmosphere RSZ flow discussed above (see Figure 1). The effects of the superposition of these wind components in the Venus upper atmosphere are: (a) to shift the divergence of the flow from the subsolar point toward the evening terminator (ET), (b) to generate larger evening terminator winds than those along the morning terminator (MT), and (c) to shift the convergence of the flow away from midnight and toward the morning terminator. These components also vary as a function of altitude and

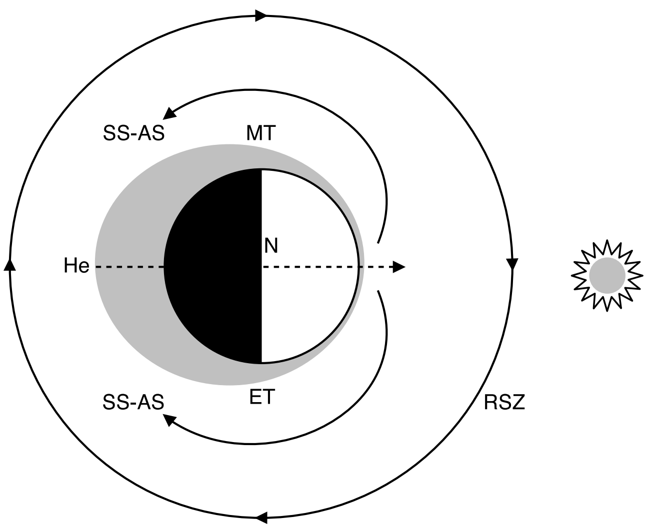

Figure 1. Sketch of the components that contribute to the upper atmospheric circulation on Venus. The sketch looks down on the north pole of the planet. The daylight hemisphere is light and the nightside hemisphere is dark. The overhead motion of the Sun is counterclockwise. SS-AS is the subsolar-antisolar circulation with upward motion and divergence under the Sun and sinking flow and convergence on the night side. RSZ is the retrograde superrotating zonal circulation which is clockwise, opposite to the overhead motion of the Sun. The lightly shaded region represents the variation in the helium content of the upper atmosphere. The SS-AS flow transports helium from the day side to the night side resulting in a helium bulge on the night side. The RSZ and SS-AS winds are in the same direction at the evening terminator ET but in opposite directions at the morning terminator MT resulting in higher zonal wind velocities at the ET compared with the MT. The effect of the superposition of the RSZ and SS-AS winds is to shift the center of dayside divergence toward the ET and shift the center of nightside convergence and the center of the helium bulge toward the MT.

reflect the changing importance of underlying drivers and their day-to-day and solar cycle variations (see Table 1).

This picture of Venus upper atmosphere winds has been gleaned from a number of remote and in-situ datasets collected at the planet. A thorough examination of Pioneer Venus Orbiter neutral density (e.g., CO_2, O, He, and H) and temperature distributions above 130 km (Figure 2) has been used to constrain general circulation model simulations, from which SS-AS and RSZ wind magnitudes can be extracted (see review by *Bougher et al.*, 1997). The spatial distribution of ultraviolet night airglow emissions (e.g., NO^*) and dayglow emissions (e.g., atomic O), and H-Lyman-alpha emissions, have all been used to trace the circulation patterns at thermospheric altitudes above ~115 km (see Table 1). Finally, visible and infrared O_2 nightglow distributions from Veneras 9 and 10, Pioneer Venus, Galileo, and the ground, along with minor species distributions (e.g., CO) have also been used to constrain upper mesospheric wind patterns (~90–110 km altitude). In addition, direct wind velocities were also obtained from CO mm observations (see review by *Lellouch et al.*, 1997). Many of these datasets are discussed in detail in *Bougher et al.* (1997) and *Lellouch et al.* (1997), and are summarized in Table 1.

The processes responsible for maintaining (and driving variations in) the SS-AS and RSZ winds in the Venus upper atmosphere are still not well understood or quantified. For example, it is apparent that some type of deceleration mechanism is necessary to slow the upper atmosphere winds (e.g., *Alexander*, 1992; *Zhang et al.*, 1996; *Bougher et al.*, 1997). This is evident since the day-to-night upper atmosphere circulation results in downwelling and adiabatic heating on the nightside, which must be limited to maintain the observed cold nightside temperatures (Figure 2) and density structure. This deceleration is not symmetric in local time, because as noted above the net zonal winds appear stronger at the dusk versus the dawn terminator. The mechanism responsible for this deceleration and asymmetry is thought to be gravity wave breaking and subsequent momentum and energy deposition in the Venus thermosphere (*Alexander*, 1992; *Zhang et al.*, 1996; *Bougher et al.*, 1997). The large variability of the superrotating zonal winds between 90 and 110 km altitude (*Bougher et al.*, 1997; *Lellouch et al.*, 1997) may arise from the changing nature of this wave breaking. However, only limited observations of gravity wave features are available to constrain the sources, their vertical propagation, and impacts at thermospheric heights (e.g. *Bougher et al.*, 1997).

A number of circulation models have been constructed to address the Venus upper atmosphere circulation (see review by *Bougher et al.*, 1997). These multi-dimensional models serve both to reproduce the global wind tracers defined above (thereby constraining the wind magnitudes) and to

Table 1. Upper Atmosphere Wind Constraints

Species/Emissions/Temps.	Altitude Range (km)	SS-AS Winds (m s^{-1})	RSZ Winds (m s^{-1})
Temps. (IR and Occultation)[a]	70–90		variable (weak)
CO mm, CO distribution[b]	90–105	present	variable (weak, occas. strong)
CO mm, winds[c]	90–105	≤ 40–110 ± 20	35–132 ± 10 (variable)
10-micron, CO_2 heterodyne[d]	109 ± 10	120 ± 20	25 ± 15 (weak)
O_2 IR (1.27-microns)[e]	95–110		highly variable ($\sim$10–50)
CO 4.7-micron, winds[g]	100–110		sum $= 140 \pm 45$
O_2 visible (400–800 nm)[f]	100–130		weak (≤ 30)
NO nightglow (UV)[g]	115–150	$\sim$200	40–60
O dayglow (130 nm)[h]	130–250		eddy diffusion
Temps. (night)[i]	above 150	$\sim$ 200	$\sim$50–100
H dayglow (121.6-nm)[j]	above 150		$\sim$45–90
H and He densities[k]	above 150		$\sim$45–90

[a] *Taylor et al.* (1980), *Kliore* (1985), *Schäfer et al.* (1990), *Roos-Serote et al.* (1995)
[b] *Gulkis et al.* (1977), *Schloerb et al.* (1980), *Clancy and Muhleman* (1985) *Clancy and Muhleman* (1991), *Lellouch et al.* (1994), *Gurwell et al.* (1995), *Rosenqvist et al.* (1995), *Lellouch et al.* (1997)
[c] *Shah et al.* (1991), *Rosenqvist et al.* (1995), *Lellouch et al.* (1997)
[d] *Goldstein et al.* (1991)
[e] *Crisp et al.* (1996), *Bougher et al.* (1997),
[f] *Krasnopolsky* (1983), *Bougher and Borucki* (1994)
[g] *Stewart et al.* (1980), *Gerard et al.* (1981), *Bougher et al.* (1990)
[h] *Alexander et al.* (1993)
[i] *Keating et al.* (1980), *Mayr et al.* (1980), *Niemann et al.* (1980) *Bougher et al.* (1986, 1997), *Mengel et al.* (1989)
[j] *Paxton et al.* (1985, 1988a,b)
[k] *Niemann et al.* (1979), *Brinton et al.* (1980)

characterize the day-to-day variability of these circulation patterns. Gravity wave breaking has been implemented in some of these model simulations to slow large scale winds. However, it has been difficult for 3-D thermospheric circulation models to reproduce observed diurnal density, temperature, and airglow variations with a unique set of input parameters and wind fields (*Bougher et al.*, 1997).

2 MAJOR UNRESOLVED QUESTIONS

2.1 Lower Atmosphere

2.1.1 Superrotation. The deep atmosphere might hold the key to the driving mechanism of the superrotation. However, it is this region of the atmosphere that we know the least about. The stratification in the lowest scale height is basically undetermined. All four Pioneer Venus probes failed to obtain thermal structure measurements in this region, and the only profile with sufficient vertical resolution to investigate static stability is that obtained by the VEGA 2 lander (*Crisp and Titov*, 1997). Thus, the latitude-longitude variation of thermal structure and static stability in the lowest scale height are unknown. Dynamical processes affected by lower atmosphere thermal structure include the strength of surface stresses that transfer angular momentum between surface and atmosphere, boundary layer convection, generation and propagation of atmospheric waves, and slope winds (*Gierasch et al.*, 1997). Detailed modeling of atmosphere-surface interactions should at least shed light on which of these interactions would be the most significant. Modeling of these dynamical processes could guide measurement objectives in future Venus missions. Even the basic balances determining the structure of the planetary boundary layer are undetermined for slowly rotating planets. *Allison* (1992) suggests that Titan's rotation is strong enough and its near-surface winds are weak enough to anticipate a geostrophic sublayer and thus a classical Ekman wind spiral structure, and the Huygens Doppler Wind data appear to bear this

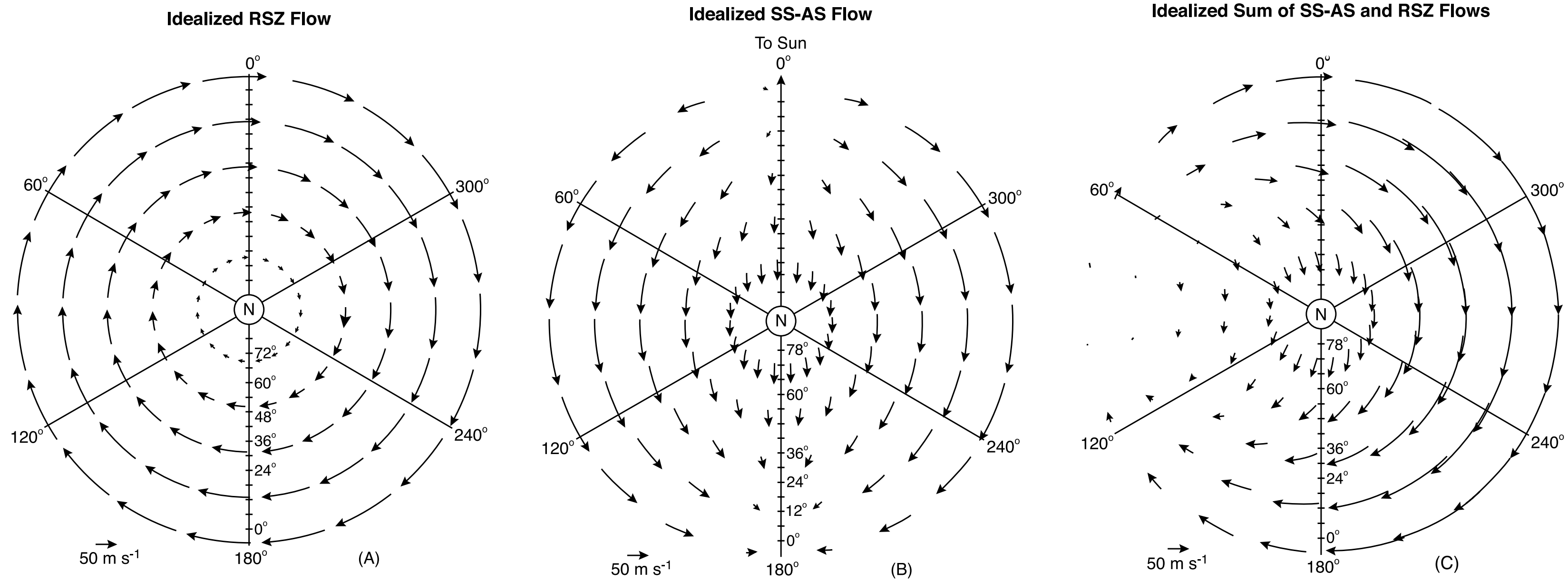

Figure 2. Retrograde superrotating zonal (RSZ) flow (a), idealized subsolar–antisolar (SS–AS) flow (b), and the sum of the two flows (c). The SS–AS flow varies as the sine of the solar zenith angle: $u = u_{\max}\sqrt{1 - \cos^2\lambda\cos^2\phi}$, where ϕ = north latitude, λ = east longitude, and = $(\phi, \lambda) = (0, 0)$ at the subsolar point. The direction of the flow is $\underline{\hat{r}} \times (\underline{\hat{r}} \times \underline{\hat{x}})$ where $\underline{\hat{r}}$ is a unit vector pointing from the center of the planet to the field point and $\underline{\hat{x}}$ is a unit vector pointing from the center of the planet to the Sun (so that the cosine of the solar zenith angle is given by $\underline{\hat{r}} \cdot \underline{\hat{x}} = \cos\lambda\cos\phi$. This flow direction has (un-normalized) vector components $\{0, \cos\lambda\sin\phi, \sin\lambda\}$ in the $\left\{\underline{\hat{r}}, \underline{\hat{\phi}}, \underline{\hat{\lambda}}\right\}$ basis. The idealized RSZ flow is given by $u = -u_{\max}\cos\phi\,\underline{\hat{\lambda}}$. The maximum values of the SS–AS and RSZ flows are set equal.

out (*Bird et al.*, 2005), but the existence of such a regime is problematic for the more slowly rotating Venus. Existing GCMs applied to Venus typically simplify the surface turbulent transfer using constant transfer coefficients, i.e., they assume that surface transfer of heat is proportional to the difference in temperature between the surface and the immediately overlying atmosphere, together with an analogous formulation of surface frictional drag on wind. Nonlocal turbulence schemes, which have improved several terrestrial climate GCMs, may be needed to allow convectively generated near-surface turbulence to efficiently interact with the free-atmosphere Hadley circulation. The altitudes at which GCM-derived winds diverge from the observed zonal wind profile (in the lowest scale height, or above, or at all heights) could be indicative of whether the simulation of the surface-atmosphere interaction or the larger-scale dynamical transport mechanisms at higher altitude is the primary problem. Although measured winds on Venus are retrograde at all altitudes, prograde surface winds are required at some latitudes (if the surface and atmosphere are in equilibrium) to guarantee zero net surface torque and provide a means for angular momentum to be supplied to the atmosphere. The latitudinal profile of surface wind may thus be a useful diagnostic for evaluating the superrotation mechanisms in different GCMs.

Not only 3-D circulation but also solar and infrared radiative transfer, cloud dynamics, and chemistry must eventually be included in models of the Venus atmosphere. (The latter two and near-surface processes are the current emphasis in Earth atmosphere GCM development.) No Venus atmospheric circulation model yet incorporates realistic radiative transfer schemes or attempts to account interactively for the effects of the ubiquitous clouds. Clearly, the heating of the atmosphere by radiative transfer and the influence of the clouds on this process drive the atmospheric circulation. Realistic radiative driving is particularly important to simulate day-night variations (which, as discussed above, are probably important in cloud-top superrotation) and deep atmosphere forcing of the Hadley circulation.

2.1.2 Mean meridional (Hadley) circulation and eddies. We need to characterize how many thermally direct Hadley cells exist between the surface and clouds and to what latitudes they extend (*Schubert*, 1983). This bears directly on how momentum is transported vertically from the surface to accelerate higher levels of the atmosphere. It is equally important to identify dominant eddy (i.e., nonaxisymmetric) components in the atmospheric flow, and to determine how they are generated. It is unlikely that any future Venus mission would be capable of measuring eddies in the deep atmosphere because of their small magnitude and significant space-time variations. Therefore, general circulation modeling would be valuable in providing an idea of what could exist, and what regimes are most capable of affecting the superrotation.

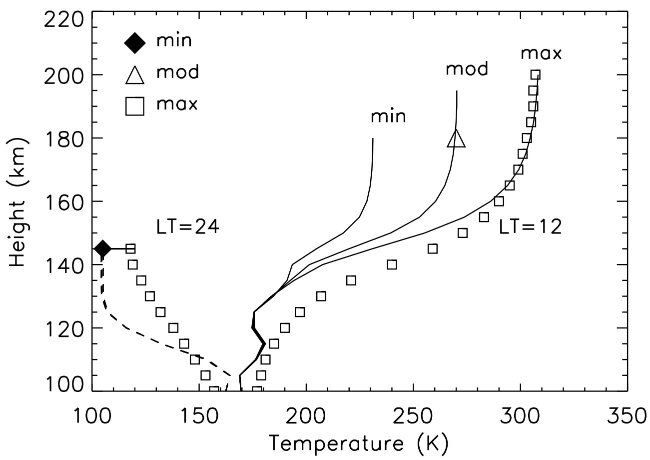

Figure 3. Venus Thermospheric General Circulation Model (VTGCM) temperatures (K) and their variations over the solar cycle. Simulated equatorial profiles are presented for noon (LT = 1200) and midnight (LT = 2400) conditions over 100 to 200 km altitude. *Hedin et al.* (1983) empirical model temperatures (solar maximum conditions) are indicated by squares. Magellan (drag) inferred temperatures (solar moderate conditions) are shown by triangles. Taken from *Bougher et al.* (2002).

A related issue involves the magnitude of thermal contrasts on constant pressure surfaces in the deep atmosphere. Theoretical considerations lead to the expectation of temperature variations of O(0.1 K) with respect to both latitude and longitude in the lowest scale height (*Stone*, 1975); simple order of magnitude estimates of day-night thermal constrasts based on solar flux measurements from Pioneer Venus (*Tomasko et al.*, 1980) yield similar values. Yet the Pioneer Venus probes indicate thermal contrasts of several degrees all the way down to near 12 km altitude, below which the probes ceased making thermal measurements (*Seiff et al.*, 1980; *Seiff*, 1983). Cyclostrophic balance above the lowest scale height is consistent with meridional temperature contrasts ≥ 1 K, but as the surface is approached the zonal wind decreases to zero, and cyclostrophic balance is no longer a good approximation. It is not clear whether RSZ flow induces measurable thermal contrasts via cyclostrophic balance, or whether the thermal contrasts are produced by some other process and subsequently induce the RSZ flow and cyclostophic balance.

Given better constraints on the latitudinal temperature contrast (and thus the vertical profile of cyclostrophically-balanced winds) and the static stability in the free troposphere, it would be possible to map the potential vorticity

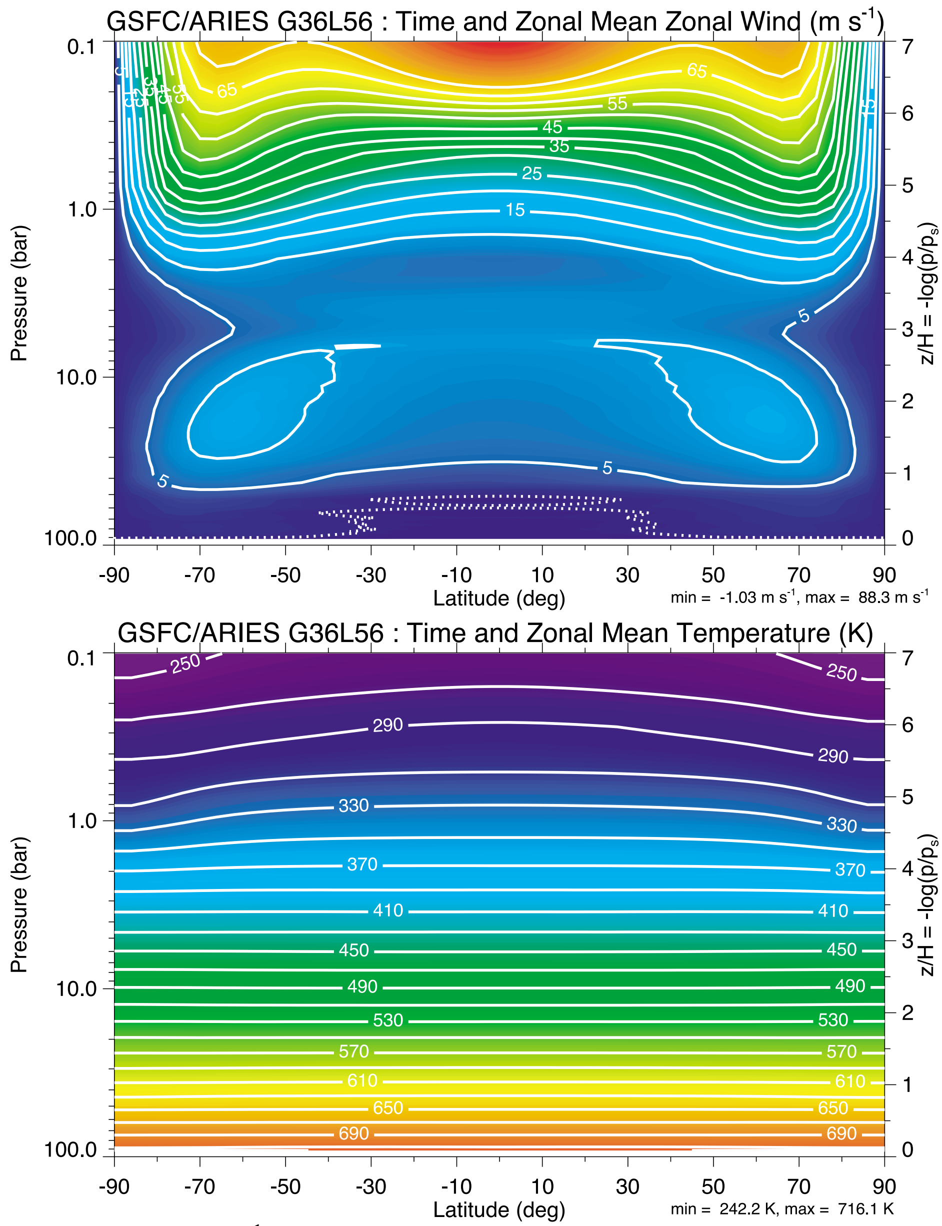

Plate 1. The mean zonal wind (m s^{-1}) and temperature (K) from a VSGCM simulation using diabatic heating similar to Yamamoto and Takahashi (2003a, 2004). Time averages are computed over the last 1000 days from a 10,000 day simulation. The contour interval is 5 m s^{-1} and 20 K in the top and bottom panels, respectively.

distribution in the Venus troposphere. Potential vorticity essentially maps the degree to which angular momentum and potential temperature surfaces intersect. Stable planetary circulations have zero potential vorticity at the equator and potential vorticity of the same sign as the Coriolis parameter in each hemisphere (*Stevens*, 1983). Baroclinic/barotropic instabilities attempt to homogenize latitudinal potential vorticity gradients equatorward of the jet regions that give rise to the instabilities, just as convection attempts to homogenize potential temperature in the vertical. Thus, depending on the efficiency of the eddies that do the mixing, near-zero values of potential vorticity may extend from the equator poleward as far as the jets. *Allison et al.* (1994) derive zero potential vorticity latitudinal profile envelopes for the zonal flow as a function of Richardson number. These represent the most efficiently latitudinally mixed state possible for a given stratification. *Allison et al.* (1994) show that the Pioneer Venus probe winds at 25 km altitude, the UV cloud-tracked winds at 62 km altitude, and the cyclostrophic thermal winds above cloud top all resemble a zero potential vorticity latitudinal profile, although our limited ability to measure the Richardson number (*Schubert*, 1983; *Gierasch et al.*, 1997) makes the inference inconclusive. This suggests that whatever processes control the Venus superrotation effectively mix potential vorticity. Potential vorticity mixing appears to operate efficiently in GCM simulations of Mars (*Barnes and Haberle,* 1996) and at Titan's rotation rate (*Allison et al.*, 1994), as well as in Earth's atmosphere (*Lindzen,* 1990). This may or may not be the case for Venus models, however, and so comparisons with zero potential vorticity profiles may be diagnostic of whether the dynamical modes that transport angular momentum equatorward are operating at maximum efficiency. This in turn may shed light on why most Venus atmosphere GCMs underestimate superrotation.

2.1.3 Vortex organization of the circulation. The vortex organization of the Venus atmosphere inferred from Mariner 10 ultraviolet images of Venus taken in 1974 (*Suomi and Limaye,* 1978) was also seen from Pioneer Venus images acquired during 1978 through 1983 (*Limaye,* 1990). The global atmosphere is organized as two hemispheric vortices centered over each pole, each exhibiting a broad mid-latitude jet and poleward flow at the ultraviolet cloud level. The vertical extent of these two vortices could not be determined from the reflected ultraviolet images. Early VIRTIS observations from the Venus Express mission indicate that the vortex organization exists deep into the Venus atmosphere. These data show the same spiral bands on the night side in the emitted infrared radiation as those seen on the day side in the ultraviolet images. Further, they also show an "S" shaped feature, akin to the features seen in the "eye" or the inner region of many tropical cyclones. This feature wasfirst detected in the Pioneer Venus thermal infrared observations (*Taylor et al.*, 1980), and was inferred as a warm feature surrounded by a cold collar. Whorls seen in the inner core region of tropical cyclones are a result of potential vorticity mixing (*Kossin et al.*, 2002), and it is possible that the "S" shaped feature seen in the core of the vortices in the north and the south polar regions are similarly produced. Prior results from tracking of the night side features seen in the Galileo near infrared images suggested poleward flow (*Carlson et al.*, 1991) at ~53 km altitude, consistent with the VIRTIS data. Thus we can surmise that the vortex circulation is deep, extending down to this level, and perhaps even deeper. We need more observations, deeper in the atmosphere and near the surface in polar regions to fully understand the vortex circulation on Venus.

Limaye (2007) has noted the similarities between a tropical cyclone and the hemispheric vortex circulation on Venus. One difference seems to be in the longevity—on Venus the vortex circulation has been observed over three decades. Although we do not have continuous spacecraft data, the vortex organization appears to have persisted throughout this period, and has existed for a long time. Tropical cyclones, on the other hand, decay when their energy source is shut down once the cyclone makes landfall. Over vast reaches of the southern oceans, cyclones generally last longer, since they can travel long distances without landfall. On Venus the vortex, being situated over the pole, does not of course "travel" with the steering winds, and the vortex never loses the energy source.

2.1.4 Thermal tides, planetary scale waves. Thermal tides have been suggested to play a role in the maintenance of the atmospheric circulation of Venus. They were detected in the thermal structure data by *Schofield and Taylor* (1983) and also in the atmospheric circulation by *Limaye* (1990). Pechman and Ingersoll (1984) and *Newman and Leovy* (1992) investigated dynamical implications, but the structure (phase and amplitude relationships) of the tides has not yet been adequately determined because of limited observations. (Thermal structure observations by the Pioneer Venus Orbiter Infrared Radiometer cover much less than one solar day, and the solar-locked structure in the cloud motions can be determined only from day-side images.) Measured cloud motions reveal inconsistencies with the theoretical calculations referenced above. Further work is needed to explore the structure of the thermal tides by both comprehensive atmospheric circulation modeling and observational data analysis (the latter incorporating the Pioneer Venus results as well as those from the Venus Express mission).

Many investigators over the years have pointed out that planetary-scale waves are suggested in whole-disk ultraviolet images of the Venus cloud tops (*Covey and Schubert*, 1981, 1982, 1983) and in the zonal winds inferred from both Mariner 10 and Pioneer Venus cloud motions (*Limaye and Suomi*, 1978; *Rossow et al.*, 1990). These waves are believed to arise from resonant oscillations and instabilities of the atmosphere, in contrast to thermal tides forced by solar heating. As with the tides, their role in the maintenance of the global circulation is suggested by theoretical models but unconfirmed due to limitations of the observations. Venus Express, with more capable instruments (see Section 4), will yield a better determination of the structure of the large scale waves.

2.2 Upper Atmosphere

The processes responsible for maintaining and driving variations in the SS-AS and superrotating wind components in the Venus upper atmosphere are not well understood or quantified. In particular, what causes the rapid and spectacular variations observed in the magnitude of the RSZ flow, especially in the upper mesosphere and lower thermosphere regions (~90–130 km altitude)? Why is the structure of the NO (UV) and O_2 (visible and IR) nightglow emissions so complex and variable with time on diurnal as well as solar cycle timescales? Why do hemispheric asymmetries in tracer emissions/species occur in the Venus upper atmosphere? Answers to these questions require many more observations to establish a comprehensive climatology of the Venus atmospheric structure and wind components over ~90–200 km altitude. A statistical assessment of the relative importance of the separate SS-AS and RSZ wind components during different atmospheric conditions can then be made.

The role of wave activity in driving these large variations in Venus upper atmosphere wind components also remains to be addressed. Gravity wave breaking is one mechanism thought to be responsible for SS-AS wind deceleration and the asymmetries resulting in the observed RSZ flow in the upper atmosphere. Constraints for gravity wave parameters at the cloud tops and above are quite limited at present. Measurements of gravity wave phase speeds and amplitudes at various altitudes are crucial to the construction and validation of gravity wave breaking models. Confirmation of this mechanism will likely require the implementation of a self-consistent gravity wave breaking formulation into three-dimensional circulation models (e.g. *Zhang et al.*, 1996; *Bougher et al.*, 1997). *Fritts and Lu* (1993) developed a gravity wave parameterization scheme for use in terrestrial GCMs based on the spectral characteristics of observed gravity waves on Earth. It has been utilized in Venus GCMs, but requires further knowledge of the gravity wave spectrum in the Venusian atmosphere (*Zhang et al.*, 1996). Other gravity wave parameterization schemes are available for possible incorporation into Venus GCMs (*Lindzen,* 1981; *Hines*, 1997; *Lawrence*, 1997; *Alexander and Dunkerton*, 1999; *Warner and McIntyre*, 2001). In short, substantial unknowns remain about the true nature of gravity waves and their impact on the dynamics of the upper atmosphere of Venus.

3 PRIORITIES FOR GENERAL CIRCULATION MODELING

3.1 Lower Atmosphere

The modeling of the general circulation of Venus' lower atmosphere has reached a peculiar state. We seem to be able to get the "right answer" (dominant RSZ flow) only if we input the "wrong reasons" (heating rates that lie outside the error margins of observation). What improvements to GCMs are needed in order to get the right answer for the right reasons? The following considerations suggest the top priorities:

1. Whatever the number and type of future missions to Venus, they will never in the foreseeable future approach the coverage that Earth's troposphere has enjoyed since the advent of routine global weather balloon observations in the mid-20th century. Accordingly, theoretical general circulation modeling will be essential both to explore mechanistic ideas and to make sense of whatever incomplete observations exist. The GCMs will necessarily include poorly constrained empirical parameters, which should be varied over their possible ranges.
2. The angular momentum of the superrotation must come from somewhere. Solar gravitational torque on the atmosphere was an early suggestion (*Gold and Soter*, 1971), but its magnitude is too small to maintain the observed RSZ flow against any reasonable dissipative processes (*Schubert* , 1983; *Gierasch et al.*, 1997). The only remaining angular momentum source is the solid planet. Thus, more precise simulation of surface-atmosphere interactions and the near-surface boundary layer is necessary. As discussed above, Earth GCMs have evolved to include detailed parameterizations of both. Analogous parameterizations for Venus would need to avoid Earth-specific assumptions like the existence of an Ekman layer and start from first principles wherever possible. A "hierarchy of models" strategy (e.g. *Andrews et al.*, 1987) proceeds from simplified to intermediate and finally to fully complex atmospheric models. Global circulation models that adapt highly simplified physics, so-called SGCMs, can help shed light on the parameters that regulate circulation regimes (Held , 2005). For example, for the terrestrial troposphere,

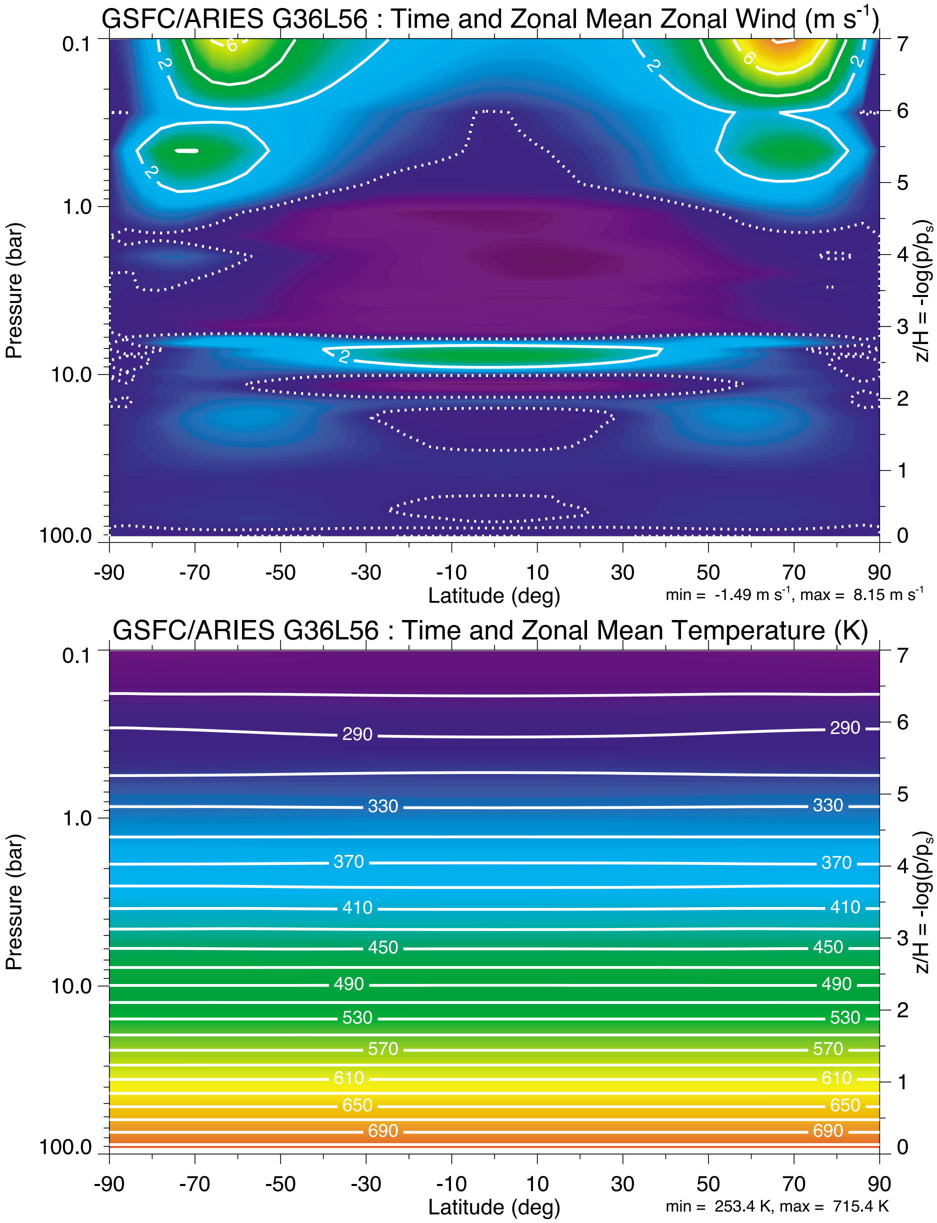

Plate 2. As in Plate 1 but for a simulation that uses a more realistic diabatic heating in the lower atmosphere (i.e., below 35 km). Contour interval for zonal wind plot is 2 m s^{-1}.

Kraucunas and Hartmann (2005) utilized an SGCM to demonstrate that persistent equatorial superrotation (i.e., west-to-east mean zonal flow over the equator) can be obtained when steady east-west variations in diabatic heating are imposed within low latitudes. The superrotation appears to be driven by quasi-stationary planetary waves that are excited by the imposed tropical heating. It might be that low-latitude topography or asymmetries in near-surface heating in the Venus atmosphere could enhance atmospheric superrotation at higher altitudes. Such mechanisms can be explored in idealized Venus SGCM simulations.

3. Superrotation in Titan's atmosphere—now confirmed by Cassini/Huygens observations, and quite possibly arising from the same dynamical mechanisms as on Venus (*Del Genio and Zhou*, 1996)—implies that particular features of Venus such as its unique surface topography might not play a critical role. On the other hand, thanks to Magellan observations, it would be a simple matter to include realistic Venus topography as a sensitivity test. Other tests could include various idealized topography boundary conditions including, of course, perfectly smooth topography. These would define what types of topography (if any) are required to efficiently transfer angular momentum from the solid planet to the atmosphere.
4. Higher horizontal resolution in Earth GCMs, up to at least 2-degree latitude/longitude grid point spacing, leads to substantially better agreement not only with small-scale details but also with large-scale flow observations (*Duffy et al.*, 2003). Venus GCMs have never had less than about 5-degree grid point spacing. This relativelycoarse resolution is adequate to represent large-scale horizontal waves such as those important in the Gierasch-Rossow-Williams mechanism of superrotation (*Del Genio and Zhou*, 1996), but it is not clear which waves are important in the real Venus atmosphere. In the vertical dimension, both theory (*Gierasch et al.*, 1997) and practical experience imply that at least several dozen levels from the surface to the model top are needed. It is not clear that the current state-of-the-art vertical resolution (50 levels) represents convergence, however, or even that it is adequate to accurately represent vertically propagating atmospheric tides. Evidently experimentation with higher resolution in both horizontal and vertical dimensions is called for.
5. No Venus GCM models yet incorporate realistic radiative transfer schemes or attempt to account for the effects of the ubiquitous clouds. Clearly, the heating/cooling of the atmosphere by radiative transfer and the influence of the clouds on this process drive the atmospheric circulation. These phenomena might need to be realistically simulated in order to get the dynamics correctly.

3.2 Upper Atmosphere

Three-dimensional modeling tools are presently being used to study the Venus upper atmosphere circulation and the tracer emissions/species distributions (see reviews by *Bougher et al.*, 1997, 2002). Both the NCAR Venus Thermospheric General Circulation Model (VTGCM) (e.g. *Bougher et al.*, 1988) and the GSFC SRM Model (e.g. *Mengel et al.*, 1989) have been used extensively to address Venus thermosphere structural and dynamic properties. These GCMs are also crucial to synthesizing the various density, temperature, and airglow datasets for extracting winds. For instance, VTGCM simulations have been conducted to reproduce the observations of the various visible, UV and IR airglow distributions (e.g. *Bougher and Borucki*, 1994; *Bougher et al.*, 1990, 1997) thereby providing an estimate of the underlying SS-AS and RSZ wind components that vary over time (see Plate 3). Solar maximum VTGCM simulations with prescribed RSZ winds (up to ~50 m s^{-1}) reveal a net flow pattern containing mean horizontal winds which are strongest across the evening terminator and converge after midnight, near the equator. However, all existing GCMs are presently unable to reproduce the observed diurnal density, temperature, and airglow variations utilizing a unique set of wind fields, eddy diffusion coefficients, and wave drag parameters (*Bougher et al.*, 1997). This may reflect missing physical processes or inputs, e.g., exospheric transport above 180–200 km altitude, planetary waves, and limited gravity wave constraints for wave breaking. In general, too many free parameters presently exist.

The upper atmosphere modeling task would be greatly improved if simultaneous wind, temperature, and density measurements could be made over ~65–200 km altitude and gravity wave parameters could be quantified. Specific upgrades needed for Venus upper atmosphere models include the following:

a Extend circulation models to cover the region above the cloud tops to the exobase (~65–200 km altitude). This extension permits a likely gravity wave source region (e.g., cloud tops), propagation region (above the cloud tops), and dissipation region (upper mesosphere and lower thermosphere) to be captured in the same three-dimensional model domain.

b Drive the upper atmosphere GCM lower boundary at cloud tops with an empirically based circulation (winds specified).

c Implement a modern gravity wave breaking model into the Venus upper atmosphere GCMs. Make use of the best available gravity wave parameters. Internally consistent momentum drag and eddy diffusion terms can then be simulated.

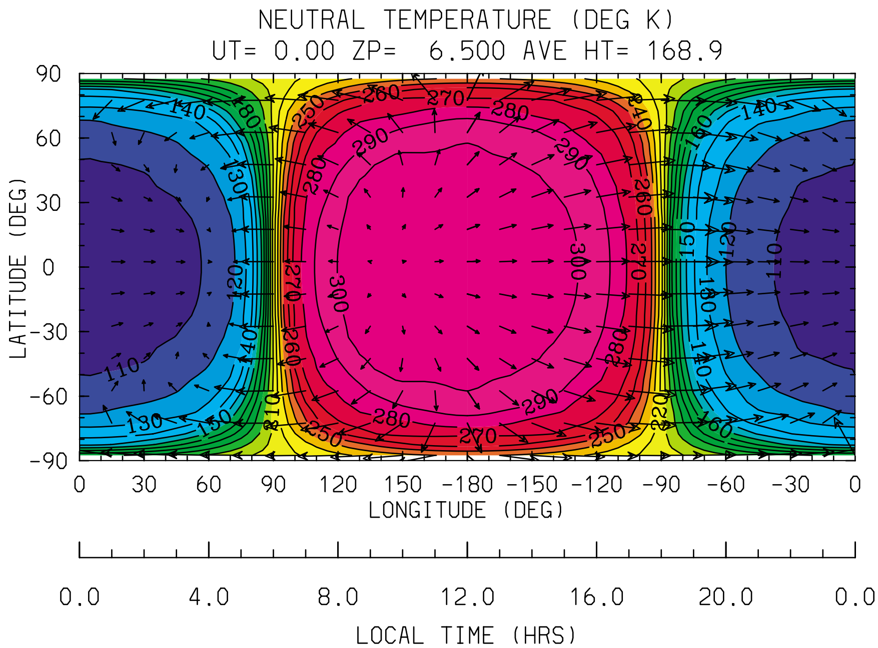

Plate 3. Venus Thermospheric General Circulation Model (VTGCM) exobase temperatures (K) and superimposed horizontal wind vectors at the ~7.5 × 10^{-3} nanobar level.Solar maximum conditions are illustrated, consistent with early Pioneer Venus obser vations. Maximum horizontal wind vectors are indicated across the evening terminator (~260 m s^{-1}). Convergence of the flow is seen after midnight, toward the morning terminator. RSZ wind speeds of ~50 m s^{-1} are prescribed at this level. Exospheric temperatures range from a nightside minimum (104 K) to a dayside maximum (308 K) yielding a day-night contrast of about 200 K, similar to that observed by Pioneer Venus instruments.

d Utilize the latest ion-neutral reaction rates of Fox and Sung (2001) for photochemistry in upper atmosphere GCM codes.
e Use SOLAR2000 fluxes to calculate the solar heating, dissociation, and ionization rates (*Tobiska et al.*, 2000)

3.3 Lower and Upper Atmosphere

The model improvements summarized in Table 2 would produce a high-resolution Venus GCM including atmospheric circulation, cloud formation and dissipation, solar and infrared radiative transfer, the near-surface boundary layer, the upper atmosphere, and interactions among these components (chemical effects have not been included). All of these improvements need to be tested, in order to determine the sensitivity of "the real superrotation mechanism" and other features of the Venus atmosphere circulation (e.g., SS-AS flow, Hadley circulation and day-night variations) to parameters that observations cannot fully determine. Such a program of model development and testing implies substantial use of computer resources.

Table 2. Atmosphere-Related Features in Current Models.

	2006-vintage GCMs	**Available Observations**	**Model Requirements***
Topography	Flat**	Height variations at 20/1 km resolution (horizontal/vertical)	Very fine horizontal/vertical resolution near surface
Surface and lowest-level atmosphere properties	Highly idealized surface interaction	Temperatures and images from surface in the visible	Direct surface-atmosphere coupling; boundary layer sub-model
Horizontal variations in atmosphere	$\sim$ 500 km grid-point spacing	$\sim$ 5—20 km (T) and $\sim$ 100 km (wind) at and above clouds	$\leq$ 100 km grid-point spacing
Vertical variations in atmosphere	$\sim$ 2 km vertical-level spacing	$\sim$ 0.1 km (T) and $\sim$ 1 km (wind) at select locations	$\geq$ 100 levels between surface and 100 km altitude
Clouds	Omitted***	Vertical profiles of particle sizes; horizontal "slices" of cloud properties	Interactive cloud simulation
Heating/cooling rates	Assumed	Vertical profiles of temperatures, fluxes at select locations	Interactive radiative transfer
Upper atmosphere	Upper atmosphere model coverage $\geq$ 100 km altitude****	Up to $\sim$ 200 km altitude	Single GCM (0–200 km). Extend upper boundary; add gravity wave parameterization and non-LTE physics

*What is needed for models to achieve the level of detail in the observations
**Except for *Herrnstein and Dowling* (2007) and *Yamamoto and Takahashi* (2006b).
***Models generally impose radiative effects of clouds directly, without explicitly including the clouds.
**** Separate upper (90–200 km altitude) and lower atmosphere models are presently used.

4 IMPACT OF ONGOING AND FUTURE OBSERVATIONS

In 2005 the European Space Agency's Venus Express (VEX) mission began observing the planet from a highly elliptic polar orbit. A major goal of VEX is to increase our understanding of the circulation and dynamics of the atmosphere from the surface up to the exobase (*Titov et al.*, 2001, 2006). VEX remote sensing measurements complement and extend those obtained by the Pioneer Venus Orbiter (PVO) between 1978 and 1992 and the Galileo flyby in 1990. VEX will permit the first detailed study of middle and upper atmosphere dynamics using O_2 (visible and IR nightglow), NO (UV nightglow), O (UV dayglow) and H (UV dayglow) emissions as tracers of the circulation. In addition, thermal mapping at and above cloud levels (~60–90 km altitude) can be used to derive thermal wind fields for comparison with the spatial and temporal variations in these emission features. Also, global wind fields will be obtained from cloud feature tracking. VEX measurements will thus provide a more comprehensive investigation of the atmosphere structure and dynamics over another period in the solar cycle and for variable RSZ wind conditions above the cloud tops. Our understanding of the underlying mechanism(s) responsible for maintaining and driving variations in the Venus atmosphere wind system will be significantly advanced.

Equipped with imaging (Venus Monitoring Camera, VMC) and mapping instruments (Visible InfraRed Thermal Imaging Spectrometer, VIRTIS), Venus Express probes the equatorial and southern hemisphere atmosphere from high altitudes to the surface at wavelengths from the ultraviolet to the thermal infrared (*Titov et al.*, 2006). Feature tracking in the ultraviolet and near infrared images of Venus (acquired daily by VMC at 365, 513, 965, and 1000 nm simultaneously), determines the atmospheric motions both on the day side and on the night side at two different vertical levels (~65 km altitudeon the day side from 365 nm images and ~50–55 km altitude on the day side and on the night side from 965 nm images). The VIRTIS instrument also yields cloud motions at multiple levels of the atmosphere on a daily basis over a limited region of Venus (due to a smaller field of view) but at multiple wavelengths that complement the VMC cloud tracking results.

In addition to its low resolution spectral mapping (imaging) capability (VIRTIS-M channel, 0.25–5.0 microns), the instrument provides a high spectral resolution channel (VIRTIS-H, 2–5 microns) without imaging capabilities. The latter addresses atmosphere dynamics by: (1) measuring 3-D temperature and derived thermal wind fields at 60–90 km altitude on the nightside and (2) mapping O_2 infrared and visible airglow as a tracer of the dynamics of the upper mesosphere and lower thermosphere (~95–130 km altitude). Nightside VIRTIS global maps of the strong 1.27 micron O_2 emission will also be obtained; repeated observations during several orbits of Venus Express will monitor its variability at time scales from hours to days. Finally, limb observations of 4.3-micron NLTE CO_2 emissions provide a sounding of the upper atmosphere above 100 km. These emissions could be sensitive to atmospheric perturbations produced by gravity-wave breaking.

The Venus Radio Occultation experiment (VeRa) on Venus Express measures the detailed vertical thermal structure of the atmosphere. VeRa profiles are obtained only during occultation opportunities but at high vertical resolution. They enable a composite view of the meridional thermal structure of the atmosphere from which the zonal circulation can be inferred through the assumption of cyclostrophic balance (Newman et al., 1984; *Limaye,* 1985). These inferred winds can be compared with similarly derived winds from the VIRTIS instrument (~ 60–90 km altitude on the nightside). In addition, the O_2 airglow at 1.27 microns will be monitored by limb observations, thereby characterizing the variations in the airglow layer over ~ 95–110 km altitude (see Table 1). Finally, the VMC utilizes filters at 356 and 376-nm to image the O_2 visible nightglow. VMC O_2 visible nightglow distribution maps can be coordinated and compared with corresponding VIRTIS O_2 IR nightglow maps in order to characterize the changing RSZ wind component for overlapping layers spanning ~ 95 to 130 km (see Table 1).

The global wind fields obtained from cloud feature tracking enable the determination of circulation for comparison with GCM results (e.g., meridional profile of zonal and meridional flow, presence of large scale waves). The balanced flow results from the zonal average thermal structure provide a check on the cloud feature results for the average zonal flow, particularly the strength of the mid-latitude jet at the cloud level. Analysis of the cloud motions in solar-fixed coordinates yields information about the magnitude and phases of the diurnal and the semi-diurnal solar thermal tides. The cloud motions also provide estimates of the transport of angular momentum at a minimum of two different vertical levels (~ 65 km and ~ 50–55 km altitude). These results should be particularly useful for evaluating GCM simulations and the Gierasch mechanism for the maintenance of the angular momentum budget. They will also provide diagnostic information about the organization of the global vortex pattern seen in Mariner 10 and Pioneer Venus ultraviolet images (*Suomi and Limaye,* 1978; *Limaye,* 1985), and the stability of the smaller polar vortices observed at thermal infrared wavelengths by Pioneer Venus (*Taylor et al.*, 1980).

The SPICAV (Spectroscopy for Investigation of Characteristics of the Atmosphere of Venus) instrument is a versatile atmospheric spectrometer that consists of both UV (110–310 nm) and IR (0.7–1.7 micron) channels (*Titov et al.*, 2001, 2006). SPICAV (UV) makes nadir, limb, and solar/stellar occultation measurements. It provides measurements of the vertical profiles of atmospheric density (and inferred temperatures) over 80–180 km altitude (dayside) and 80–150 km altitude (nightside) via stellar occultations. These day-to-night density and temperature variations can be used to validate GCM simulations and thereby extract thermospheric SS-AS wind magnitudes. Airglow (nadir and limb) observations of NO (190–270 nm), O (130.4 nm), H (121.6 nm), and CO (Cameron band) emissions are also made. Near apoapsis viewing of the nightside will provide global spectral imaging sequences of these airglow features, enabling maps to be constructed, from which estimates of the changing thermospheric RSZ wind component (above ~ 115 km altitude) can be made. Periapsis limb viewing (e.g., the NO emission layer), at high vertical resolution, will provide further constraints on the changing nature of the local chemical and eddy diffusion processes on the nightside that regulate the nightglow intensity and its vertical distribution.

SPICAV (IR) is a miniature IR spectrometer (with 0.5–1.0 nm spectral resolution). This instrument monitors the 1.27 micron emission with limb viewing. This high vertical resolution profile of the airglow layer, when combined with corresponding O_2 nightglow maps from VIRTIS provides a more comprehensive picture of the O_2 nightglow's vertical and horizontal distributions.

VEX datasets can be assimilated to constrain GCMs, from which separate SS-AS and RSZ wind components can be extracted. A greatly expanded climatology of the Venus upper atmosphere structure and wind components will thus be compiled. In addition, gravity wave parameters above the cloud tops will be measured (or inferred) and used to constrain the gravity wave breaking model proposed by Alexander (1992). The feasibility of the gravity wave mechanism for regulating the SS-AS and RSZ wind components can then be tested.

The Venus Climate Orbiter (VCO) is a mission proposed to be launched by Japan in 2010 (*Nakamura et al.*, 2007). By making observations of Venus at ultraviolet and near infrared wavelengths from an equatorial, elliptic orbit, VCO will provide observations complementary to those from Venus Express. By the choice of the VCO orbit, with the spacecraft moving in the same direction in the equatorial plane as Venus, VCO will be able to focus more on the short term evolution of the clouds and the concurrent atmospheric circulation and thus provide more information on small scale and short term processes not possible from previous missions. It will provide a good picture of the atmospheric circulation at low and middle latitudes, but it will miss the polar latitudes. Since VCO is planned to arrive at Venus just as the Venus Express mission will be nearing its end, we will have observations of the Venus atmospheric circulation over a long period of time, from 2006 through perhaps ~ 2013, yet the lack of overlap is disappointing.

The Messenger spacecraft flies by Venus in October 2006 and June 2007 on its way to Mercury. It is planned to image the upper cloud layers at visible and near-infrared wavelengths to compare with previous observations. Coordination with VEX could enable some unique simultaneous measurements.

Venus Express, the Messenger flybys, and Venus Climate Orbiter will provide a wealth of new observations to both constrain and evaluate GCM models of atmospheric structure and dynamics. The new data will restore balance between observation and theory in our quest to understand the workings of the Venus atmosphere.

5 CONCLUDING REMARKS

Cloud-top superrotation surprised Venus observers nearly half a century ago. Explaining it—and how it transitions to SS-AS flow in the upper atmosphere—would clear up a long-standing mystery of atmospheric dynamics, and lead to a comprehensive, self-consistent picture of Venus' atmospheric circulation and how it is forced. Not only solar/infrared radiative transfer and 3-D circulation but also cloud dynamics, near-surface processes, and—eventually—chemistry at all levels must be included in models of the Venus atmosphere. (The latter three are the current emphasis in Earth atmosphere GCM development.) Accomplishing this goal is a necessary condition for tackling the "big questions" about how Venus' climate evolved so differently from Earth's. Understanding terrestrial planets and their climatology has become a principal focus of NASA's Astrobiology program through that program's emphasis on studying habitable planets. The Kepler Mission to be launched in 2008 will search over 100,000 stars in an attempt to determine the frequency of existence of Earth-sized planets. A major scientific goal will be to determine whether those planets lie in the habitable zone of the parent star. A planet's atmospheric circulation could be a critical factor in determining a planet's habitability (Joshi et al., 1997). In size and mass Venus is very similar to Earth. Not to understand Venus' atmospheric superrotation, which is such a fundamental feature of this terrestrial planet's dynamic circulation, casts doubt on how well we can assess planet habitability in general, and to what extent we understand dynamic meteorology for situations other than our own planet.

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