Venus Upper Atmosphere Circulation Models and Coupling from Above and Below

Stephen W. Bougher
University of Michigan
(bougher@umich.edu)
(734-647-3585)
Current Picture of Upper Atmosphere Circulation (~90-200 km)

- Stable subsolar-to-antisolar (SS-AS) cell
  - Density, temperature & airglow constraints (e.g. PVO)
  - Wind magnitudes: \( \leq 200 \text{ m/sec} \) (stable over time)
  - Solar (EUV-UV-IR) driven
  - Requires momentum drag on pressure driven winds

- Retrograde superrotating zonal (RSZ) flow
  - Density, temperature & airglow constraints (PVO, Gnd)
  - Wind magnitudes: \( \sim 0-130 \text{ m/sec} \) (highly variable)
  - Cyclostrophic balance and latitudinal T-gradients
  - Lower atmosphere coupling (GW & tidal impacts)
Cartoon of Venus Upper Atmosphere SS-AS Wind Component. Mengel et al., [1989]

Add clockwise (RSZ) winds yielding net flow pattern
Upper Atmosphere Densities and Temperatures:
Mengel et al. [1989]
Upper Mesosphere CO Density Distributions: Gurwell et al., [1995]
Averaged PVO Nitric Oxide Nightglow (UV): Bougher et al. [1990]
Variable Nitric Oxide Nightglow (UV): Bougher [1980]
PVO Star Tracker O$_2$ Visible Nightglow: Bougher and Borucki [1994]

~0.3 kR Intervals
Ground-based $O_2$ IR Nightglow Observations: Ohtsuki et al. [2005]

- Dynamical probe of 90-115 km region
- December 21, 2002 observations. Image cubes of the 1.27$\mu$m Q-branch. Okayama Astrophysical Observatory, Japan.
- Brightest feature at ASP (~5MR), which overlaps warmest temperatures in region (~193±9 K spot, 175±25K surrounding)
- Simultaneous brightness and temperature measurements suggests strong adiabatic heating at ASP owing to strong subsidence of circulation (and/or chemical recombination).
- Implies strong local downdrafts can modify SS-AS plus RSZ influence upon $O_2$ IR nightglow distribution. Intermittent spots.
### Upper Atmosphere Wind Constraints (~90-200 km):

**Summary**

<table>
<thead>
<tr>
<th>Species/Emissions/Temperatures</th>
<th>Altitude Range (km)</th>
<th>SS-AS Winds (m/sec)</th>
<th>RSZ Winds (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperatures (IR and Occultation)</strong>&lt;sup&gt;a&lt;/sup&gt;</td>
<td>70-90</td>
<td></td>
<td>Variable (weak)</td>
</tr>
<tr>
<td>CO mm, CO distribution&lt;sup&gt;b&lt;/sup&gt;</td>
<td>90-105</td>
<td>Present</td>
<td>Variable (weak, occas. strong)</td>
</tr>
<tr>
<td>CO mm, winds&lt;sup&gt;c&lt;/sup&gt;</td>
<td>90-105</td>
<td>≤40-110 ±20</td>
<td>35-132 ±10 (variable)</td>
</tr>
<tr>
<td>10-micron, CO&lt;sub&gt;2&lt;/sub&gt; heterodyne&lt;sup&gt;d&lt;/sup&gt;</td>
<td>109 ±10</td>
<td>120 ±20</td>
<td>25 ±15 (weak)</td>
</tr>
<tr>
<td>O&lt;sub&gt;2&lt;/sub&gt; IR (1.27-microns)&lt;sup&gt;e&lt;/sup&gt;</td>
<td>95-110</td>
<td></td>
<td>Highly variable (~10-50)</td>
</tr>
<tr>
<td>CO 4.7-micron, winds&lt;sup&gt;g&lt;/sup&gt;</td>
<td>100-110</td>
<td></td>
<td>Sum=140 ±45</td>
</tr>
<tr>
<td>O&lt;sub&gt;2&lt;/sub&gt; Visible (400-800 nm)&lt;sup&gt;f&lt;/sup&gt;</td>
<td>100-130</td>
<td></td>
<td>Weak (≤30)</td>
</tr>
<tr>
<td>CO 4.7-micron, winds&lt;sup&gt;g&lt;/sup&gt;</td>
<td>125-145</td>
<td>Sum=200 ±50</td>
<td></td>
</tr>
<tr>
<td>NO nightglow (UV)&lt;sup&gt;h&lt;/sup&gt;</td>
<td>115-150</td>
<td>~200</td>
<td>40-60</td>
</tr>
<tr>
<td>O dayglow (130 nm)&lt;sup&gt;l&lt;/sup&gt;</td>
<td>130-250</td>
<td></td>
<td>Eddy diffusion</td>
</tr>
<tr>
<td>Temperatures (night)&lt;sup&gt;i&lt;/sup&gt;</td>
<td>Above 150</td>
<td>~200</td>
<td>~50-100</td>
</tr>
<tr>
<td>H dayglow (121.6-nm)&lt;sup&gt;k&lt;/sup&gt;</td>
<td>Above 150</td>
<td></td>
<td>~45-90</td>
</tr>
<tr>
<td>H and He densities&lt;sup&gt;l&lt;/sup&gt;</td>
<td>Above 150</td>
<td></td>
<td>~45-90</td>
</tr>
</tbody>
</table>

References: (a) Taylor et al., 1980; Schafer et al., 1990; Roos-Serote et al., 1995; Kliore, 1985; (b) Gulkis et al., 1977; Schloerb et al., 1980; Clancy et al., 1985a; Clancy and Muhlmann, 1991; Gurwell et al., 1995; Lellouch et al., 1994; Rosenqvist et al., 1995; (c) Shah et al., 1991; Lellouch et al., 1994; Rosenqvist et al., 1995; (d) Goldstein et al., 1991; (e) Crisp et al., 1996; Bouger et al., 1997; (f) Krasnopolsky, 1983; Bouger and Borucki, 1994; (g) Maillard et al., 1995; (h) Stewart et al., 1980; Bouger et al., 1990; Gerard et al., 1981; (i) Alexander et al., 1993; (j) Niemann et al., 1980; Mayr et al., 1980; Mengel et al., 1989; Keating et al., 1980; Bouger et al., 1986, 1997; (k) Paxton et al., 1985, 1988a,b; (l) Niemann et al., 1979; Brinston et al., 1980.
Venus Upper Atmosphere GCMs

- **NCAR VTGCM** (Venus Thermospheric General Circulation Model)
  - Bouger et al. [1988; 1990; 1996, 1997; Bouger and Borucki, 1994]
  - 3-D, finite difference, time dependent
  - Neutrals (CO$_2$, CO, O, N, N$_2$, O$_2$, He,) & ions, 3-component winds.
  - ~95-200 km

- **SRM** (GSFC Spectral Model)
  - Mengel et al., [1989]; Stevens-Rayburn et al., [1989].
  - 3-D, spherical harmonic model
  - CO$_2$, O, He neutral species, no ions. 3-component winds.
  - ~80-200 km
VTGCM Input Parameters, Fields, and Domain

- Domain: ~90-200 km; 33-levels; 5x5° resolution
- Major Fields and Species: T, U, V, W, & O, CO, N₂, CO₂
- Minor Species: O₂, He, NO, N(4S), N(2D)
- Major Ions: CO₂+, O₂+, NO+, O+ (PCE region)
- Dayside Homopause Kzz = 1 x 10⁷ cm²/sec (at ~136 km)
- Heating: Solar EUV-UV and near IR
- Heating efficiencies: EUV = 20%; UV = 22%
- NLTE 15-µm cooling scheme from Bougher et al., [1986]. Now k(CO₂-0) ~ 3.0 x 10⁻¹² cm³/sec at 300K.
- Simplified ion-neutral chemistry (e.g. Fox and Sung, 2001)
- Airglow capability: NO (UV), O₂ (1.27-micron & visible)
- Gravity wave momentum drag (Zhang et al., 1996)
VTGCM Simulations: Equatorial Temperature Profiles
VTGCM Simulations: Equatorial Mixing Ratio Profiles

The diagram shows the relationship between height (km) and the oxygen-to-carbon dioxide mixing ratio (O/CO₂) for different LT (Local Time) values. There are curves representing minimum (min) and maximum (max) values at LT=12 and LT=24.
VTGCM SMED Simulation:
LT = 1200 Heat Balances (K/day)
VTGCM SMAX Simulation:
T+(U,V) at Homopause (~130 km)
VTGCM SMAX Simulation:
T+(U,V) at Exobase (~180 km)
Simplified Dayside Nitric Oxide Chemistry: Bougher et al. [1990].

![Diagram of simplified nitric oxide chemistry](image-url)
Bougher et al. [1997]

VTGCM: Nightglow (SMAX)

NO (0,1)-δ band: (≤1.36 KR)

O₂ Visible: (≤3.6 KR)

O₂ 1.27-micron: (≤0.7 MR)
VTGCM SMAX Simulations: Impact of Variable RSZ Winds on the O$_2$ IR Nightglow [Zhang et al. 1996]

$U_z = 0$ m/s

$U_z = 60$ m/s
VTGCM SMAX Simulation:
LT=2400 Densities (Kzz Impact)

solid curves $K_t \leq 1 \times 10^7$
dashed curves $K_t \leq 5 \times 10^7$

PVO ENTRY PERIOD
LOWEST OPERABLE PERIAPSIS

NO$^+$ NIGHTGLOW
$\lambda = 198$ nm

[113 km] [106 km] [104 km] [107 km]
VEX Measurements to Characterize the Upper Atmosphere Circulation

1. SPICAV UV and IR Measurements
   - Vertical profiles of densities (inferred T) over 80-180 km (dayside) & 80-150 km (nightside) via stellar occult.
   - Airglow (nadir and limb) observations of NO (UV), O(130.4-nm), H(121.6-nm) and CO (Cameron band), etc. emissions. Tracers of SS-AS and RSZ components.
   - High vertical resolution profiles of 1.27 micron emission with IR limb viewing of airglow layer.

2. Venus Monitoring Camera
   - Imaging of O₂ visible airglow with 356 and 376-nm filters. Tracer of RSZ wind component (~100-130 km).
VEX Measurements (Continued):

3. VIRTIS Visible and IR Measurements
   - 3-D temperature and derived thermal wind fields on the nightside (60-90 km)
   - Global maps of O₂ IR and visible airglow as a tracer of the net circulation (~95-130 km).
   - Repeated observations during several orbits will permit a monitoring of IR airglow variability at different time scales between a few hours up to several days.
   - Limb observations of 4.3-micron NLTE CO₂ emissions which may be sensitive to atmos. perturbations produced by breaking GWs. Maps of these GW perturbations?
4. **PFS IR Measurements**

- Global temperature and derived thermal wind fields above the cloud tops (~55-100 km). Zonal wind fields to be compared with VIRTIS derived thermal winds.
- Limb observations of O$_2$ IR airglow, characterizing variations in the emitting layer (~95-110 km)

5. **VeRA Temperature and Density Measurements**

- Profiles of neutral mass density, T, and pressure as a function of local time and season (~35-100 km).
- Derived thermal winds to be compared to those from VIRTIS and PFS.
Outstanding Problems & Questions:

1. Variability of Upper Atmosphere Wind Components:

- What processes are responsible for maintaining and driving variations in the SS-AS and RSZ wind components in the Venus upper atmosphere?
- What causes the rapid and spectacular variations observed in the magnitude of the RSZ flow, especially over 90-130 km?
- Why is the structure of the NO (UV) and O$_2$ (visible and IR) nightglow emissions so complex and variable with time?
- Why do hemispheric asymmetries in tracer species/emissions occur in the Venus upper atmosphere?
- Must establish a comprehensive climatology of the Venus structure and wind components over 65-200 km.
2. Limitations of Current Global Circulation Models (GCMs)

- Existing GCMs are unable to reproduce the observed diurnal density, temperature, and airglow variations using a unique set of wind fields, eddy diffusion coefficients, & wave parameters.
- Missing physics: (a) exospheric transport, (b) planetary waves, and limited GW constraints for wave breaking models.
- Presently too many free parameters!
- Must: (a) extend GCM domain to cover region of cloud tops to the exobase (~65-200 km); (b) obtain comprehensive structure and wind constraints simultaneously (e.g. wind, T, densities); and (c) quantify gravity wave parameters above the cloud tops.