Venus Atmosphere GCMs from the USA

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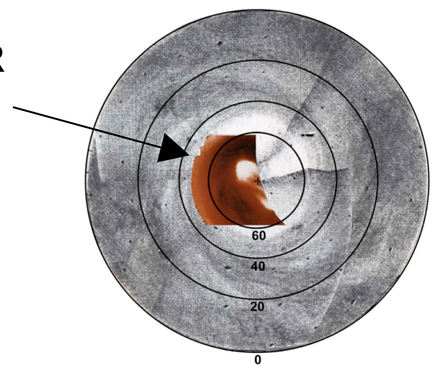
Observational Targets for Venus GCMs

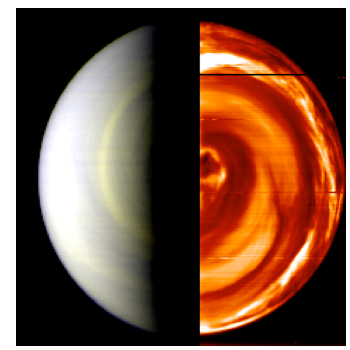
- Surprising and robust features:
  - Superrotation: the traditional target
    - Same direction of solid planet rotation (“retrograde”) *everywhere* !?
    - Calm at surface, maximum at cloud tops, transition to subsolar-antisolar flow at higher altitudes
  - Polar vortex:

Pioneer Venus IR image (1980) superimposed on Mariner 10 UV images (1974)
Figure courtesy of Sanjay Limaye



Venus Express UV and near-NIR images (2006)

Downloaded from VEXP Web site



Day side Night side

- Expected and maybe observed features:
  - Hadley cell
    - Cloud-top features drift poleward, suggesting thermally direct, equator-to-pole circulation
  - Atmospheric tides at and above clouds?
    - Classical observations (from Pioneer Venus) span < 1 solar day!
  - Other waves??
    - Rossby and Kelvin waves inferred from cloud markings in UV
    - VEGA balloons may have encountered gravity waves; also seen in radio occultations

US GCMs before the Millennium

- Confronting inadequate computer power
  - Kalnay and Charney, MIT (J Atmos Sci 30: 763, 1973 & 32: 1017, 1975)
    - 2-D: assumed symmetric about rotation axis or subsolar / antisolar line
    - Kalnay went on to direct the NCAR / NCEP reanalysis project in the 1990s. *The first person to construct a Venus GCM became a world leader in terrestrial weather prediction and climate dynamics.*
  - Young and Pollack, NASA (J Atmos Sci 34: 1315, 1979 & 37: 250, 1980)
    - 3-D, but kept only $Y_L^M(\theta, \phi)$ with $L \leq 4$ and 16 vertical levels
    - Superrotation at ~ 100 m / s, but was it a numerical artifact?
- "Slowly-rotating Earth" GCMs: Del Genio et al., NASA
  - See Icarus 101: 1 (1993) & 120: 332 (1996)
  - Required for model to obtain equatorial superrotation:
    - Higher levels decoupled from lower
    - Momentum conservation to high accuracy (double-precision makes a big difference!) -- "weakly forced / weakly dissipative system"

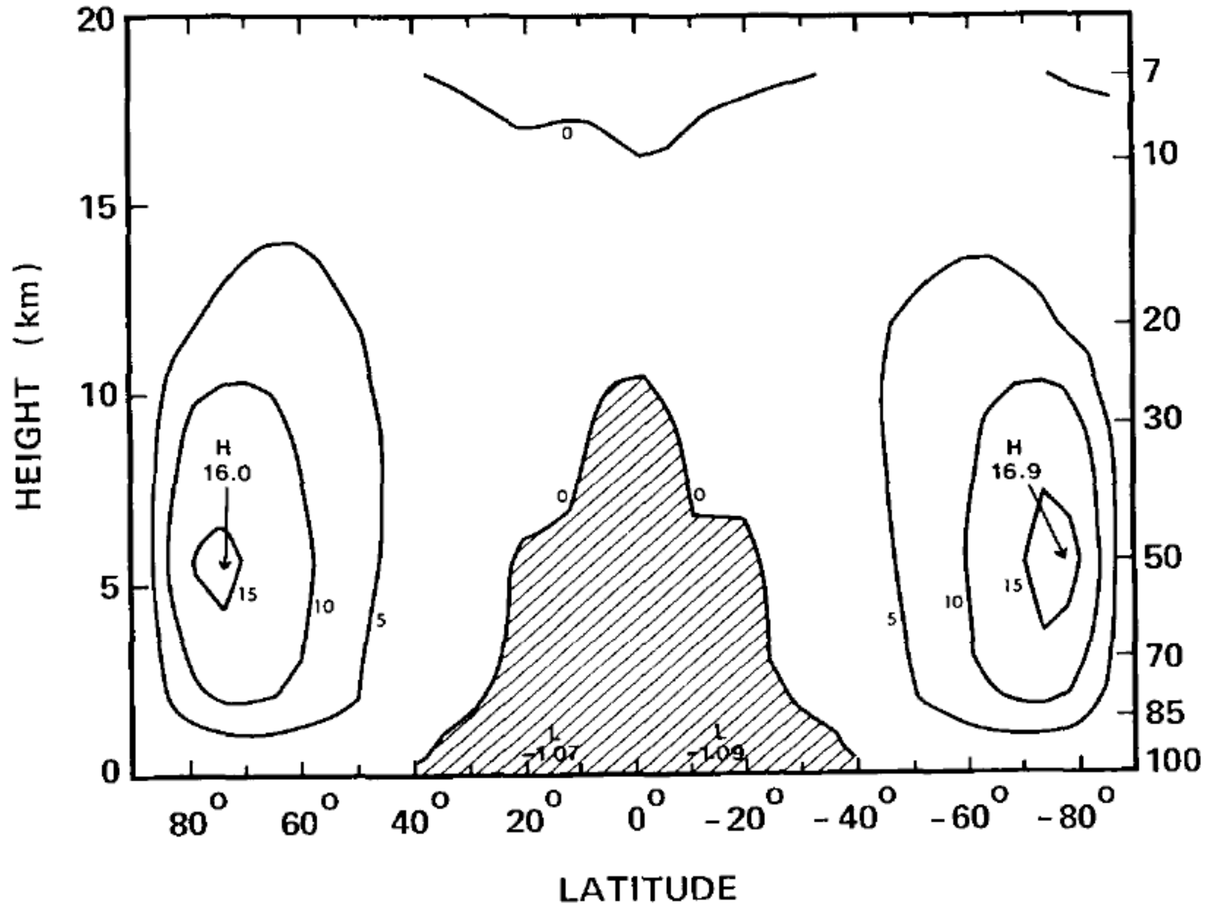
Recent Venus GCMs from the USA

- Inspired by Yamamoto & Takahashi (Japan), Lee et al. (UK)
  - Venus EPIC (Explicit Planetary Isentropic Coordinate) Model
    - Dowling et al., Comparative Planetology Laboratory, University of Louisville (Icarus 182: 259, 2006 & JGR 112, E04S08, doi:10.1029/2006JE002804, 2007)
    - "We find that the addition of topography substantially changes both the evolution and end state of the model's spin-up: the magnitude of the superrotation is diminished from 55 m s^{-1} to 35 m s^{-1}" [in contrast to Yamamoto, Takahashi & Kitoh]
  - Venus Simple-Physics GCM (modified NASA ARIES model)
    - Hollingsworth et al. (GRL 34, L05202, doi:10.1029/2006GL028567, 2007)
    - Sensitivity of results (strong vs. weak superrotation) to assumed forcing
- Adopting Earth weather-prediction / climate models to Venus
  - Venus WRF (Weather Research and Forecasting) GCM
    - Chris Lee, Cal Tech -- see last slide (www.gps.caltech.edu/~lee/presentations/lee.2007.vadw.pdf)
  - CAM (Community Atmosphere Model, a.k.a. "the NCAR model")
    - This talk's authors
    - Part of Extraterrestrial-CAM consortium (swiki.ucar.edu/cam-dev/32*)

* Use UCAS password or e-mail andrew@ucar.edu.

Results from one slowly-rotating Earth GCM

(Covey et al., Icarus 66: 380, 1986)



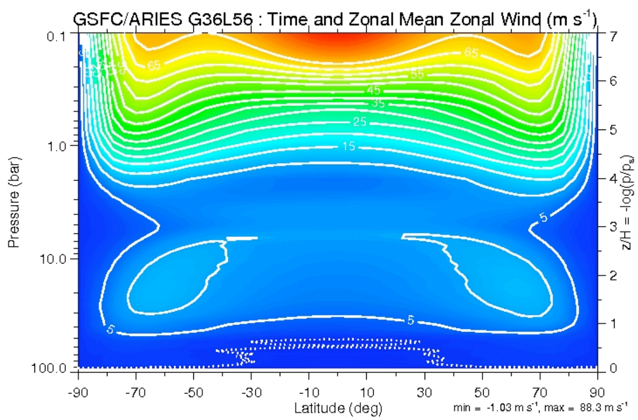
- Contour plot of mean zonal wind (in m / s) shows only weak jet streams near poles, *sub*rotation at low altitudes near equator.

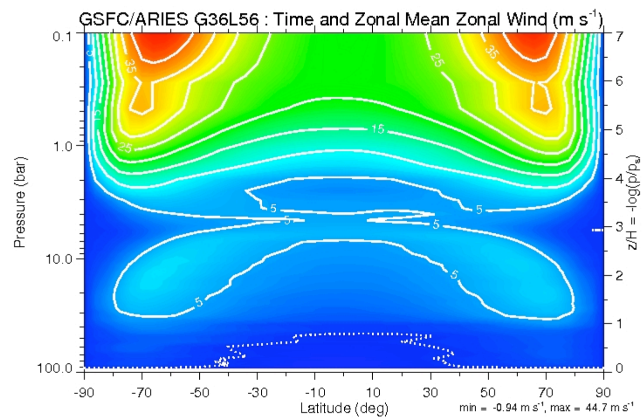
⇒ This result may be typical for VGCMs as well, before extensive spin-up and parameter "tweaking."

Some Recent Venus GCM Work

- Hollingsworth et al. 2007; based on Yamamoto and Takahashi -- “The right answer for the wrong reason, or the wrong answer for the right reason”

Mean Zonal Wind (orange / red ⇒ 70+ meters per second)





Left: the right answer (strong superrotation) for the wrong reason (assumed solar heating is too strong)

Right: the wrong answer (weak superrotation + polar jets) for the wrong reason (solar heating <u>as observed</u>*)

- How to get the right answer for the right reason? Some possibilities:
  - Including atmospheric tides (Takagi and Matsuda 2007; based on Lindzen)
  - Accurately calculating solar and infrared energy transport (Lebonnois et al. 2008)
  - Including surface topography? Maybe, but --
    - On Earth, mountains induce gravity wave *drag*.
    - VGCM numerical experiments to date get *slower* superrotation, or negligible effect.

* *<u>Caveat</u>* : observed only once!

Problem with making Earth climate GCMs extraterrestrial: "Earth-centric" sub-grid scale physics -- e.g. vertical ν_{eddy}

The formulation of the diffusive parameterization of subgrid-scale vertical processes embodied in the quantities $_V\mathbf{F}$, $_V\mathbf{F}_T$, $_V\mathbf{F}_M$ is done using a mixing length definition of the diffusion coefficient and is as follows:

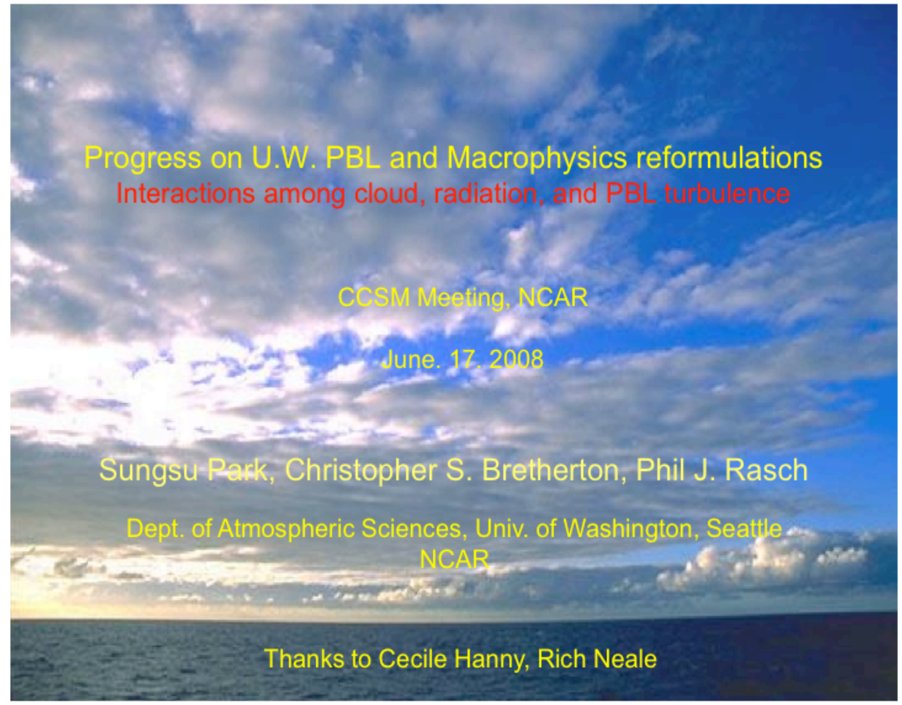
$$\{_V\mathbf{F}, {_VF_T}, {_VF_M}\} = \frac{g}{p_*}\frac{\partial}{\partial\sigma}\left\{\tau, \frac{H}{c_p}, E\right\}, \qquad (24)$$

where

$$\left.\begin{aligned} \tau &= \rho^2 \frac{g}{p_*} K_V \frac{\partial \mathbf{V}}{\partial\sigma} \\ \frac{H}{c_p} &= \delta\rho^2 \frac{g}{p_*} K_V \frac{\partial\theta}{\partial\sigma} \\ E &= \rho^2 \frac{g}{p_*} K_V \frac{\partial M}{\partial\sigma} \end{aligned}\right\}, \qquad (25)$$

Here K_V defines the vertical diffusion coefficient which is given in terms of a mixing length μ and the magnitude of the wind shear according to

$$K_V = \rho(g/p_*)\mu^2 \left|\frac{\partial\mathbf{V}}{\partial\sigma}\right|.$$



McAvaney et al. (1978, CCM0A)
- a handful of simple equations
- one adjustable parameter: mixing length
- one Fortran subroutine
- a few dozen lines of code

Park et al. (2008, CAM3.5 augmentation)
- a complex algorithm with "interactions among cloud, radiation, PBL turbulence"
- Fortran 90 module containing:
    - 8 subroutines
    - 3400 lines of code + comments (but overlaps some other CCM0A functions)

One solution -- entirely new, detailed sub-grid scale physics

e.g., radiative heating / cooling:

Since the main forcing of atmospheric circulation is absorption and emission of radiation, radiative transfer in the atmosphere of Venus should be accurately represented.

Therefore the authors of this talk are cooperating with LMD:

- We are implementing a self-consistent model of the radiative fluxes at each level in the CAM GCM.
- The model is based on the LMDZ Venus GCM (Lebonnois et al., B.A.A.S. 37: 742, 2005).
- This model includes a Net-Exchange Parameterization of the of the infrared radiation (Eymet et al. Icarus, 2008) and the short wavelength radiation parameterization of Crisp (Icarus 67: 484, 1986).

Another (temporary*) solution -- drastically simplified sub-grid scale physics

e.g. in parallel with the cooperative work with LMD, we're imposing "very simple forcing / dissipation" (Held & Suarez, BAMS 75: 1825, 1994) on CAM:

- Quite similar to approaches used by Yamamoto and Takahashi (2003, 2004) and Hollingsworth (2007).
- Initial results suggest that forcing parameters need delicate "tweaking" to get realistic superrotation.
- Are our results consistent with the earlier work cited above? If so, what are the forcing-parameter values needed for superrotation, and are they consistent with observations of radiative fluxes -- i.e. *Do GCMs have common errors? Where do these errors come from?* If not, *Why do different GCMs get substantially different results from nearly the same assumptions?*

* Temporary because we really want a single detailed and correct set of model assumptions. But Earth GCM experience implies that is very difficult!

Considerations for a Venus Model Intercomparison Project (VMIP)

- Some limited VMIPs are already happening.
  - GFDL FMS, Oxford VGCM and VenusWRF (www.gps.caltech.edu/~lee/presentations/lee.2007.vadw.pdf)
  - FMS and VenusCAM (John Wilson [GFDL] and Helen Parish)
- Much relevant experience for an expanded VMIP exists:
  - CMIP: the Coupled [ocean-atm] Model Intercomparison Project
    - Latest phase (using IPCC AR4 model output) is too big to be a prototype for a startup MIP.
    - See www-pcmdi.llnl.gov/projects/cmip for earlier phases.
  - OCMIP: the Ocean-Carbon Model Intercomparison Project
    - Database management was largely a one-FTE effort (Jim Orr [orr@lsce.saclay.cea.fr]) but very well organized.
  - 41(!) other MIPs listed on the Web at www.clivar.org/organization/wgcm/projects.php
- The PCMDI can give advice (and software) but *cannot* participate.

One of many software packages developed and maintained by PCMDI:

Climate Model Output Rewriter (CMOR)
http://www2-pcmdi.llnl.gov/cmor

The "Climate Model Output Rewriter" (CMOR, pronounced "Seymour") comprises a set of FORTRAN 90 functions that can be used to produce CF-compliant netCDF files that fulfill the requirements of many of the climate community's standard model experiments. These experiments are collectively referred to as MIP's and include, for example, AMIP, CMIP, CFMIP, PMIP, APE, and IPCC scenario runs. The output resulting from CMOR is "self-describing" and facilitates analysis of results across models. Much of the metadata written to the output files is defined in MIP-specific tables, typically made available from each MIP's web site. CMOR relies on these tables to provide much of the metadata that is needed in the MIP context, thereby reducing the programming effort required of the individual MIP contributors.

For questions concerning CMOR, contact Karl Taylor (taylor13@llnl.gov).

- CMOR Version 1 was used for the IPCC AR4 climate-model output.
- CMOR Version 2 will be used for the IPCC AR5 climate-model output.