SUPERROTATION IN A VENUS GCM WITH REALISTIC RADIATIVE FORCING

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Introduction

The ongoing ESA Venus Express mission and the first solar transits of Venus of the spacecraft era have spurred renewed interest in the dynamical nature of this exotic terrestrial atmosphere. At the same time, increased computing power and more advanced numerical modeling techniques have allowed conceptual and analytical models of the atmosphere to be tested simultaneously within nonlinear numerical models.

Early studies of the Venus atmosphere showed a large scale circulation dominated by atmospheric superrotation and an extremely hot and dense lower atmosphere. Analytical models suggested complex wave/mean-flow interactions dominate the circulation in the upper atmosphere, with IR heating maintaining the hot lower atmosphere. Distinguishing precisely which mix of wave processes is of primary importance to understand the circulation but is not possible with analytical models alone.

Increases in computing power allowed longer-timescale and slower rotating atmospheres to be studied numerically in the 1990's [1]. However, it was only in the mid 2000's that it was shown [2,3] that modern GCMs are able to reproduce elements of the atmospheric circulation. These simplified GCMs retained Newtonian relaxation in lieu of radiative transfer, and the timescales used for practical simulations were much shorter than those for the real system. Regardless, these models suggested that a mixture of mean overturning circulation and planetary scale wave activity could yield somewhat Venus-like circulations. These simplified GCMs do not solve the problem of Venus' circulation, however, because of the deliberate use of simplified radiative forcing and missing sub grid-scale and boundary layer processes. Several additional modeling efforts with simplified forcing have subsequently also found superrotation without exact replication of the observations.

It is clear that implementing more physically-based radiative heating is the crucial next step. Not only is realistic radiative forcing critical, but also more physically-based radiative transfer is essential for introduction of other physical processes, like cloud and haze effects. In this vein, since 2008 multiple groups [4,5,6] have developed Venus GCMs with increasingly complex and realistic physical parameterizations with the goal of using these more complete models along with data to constrain the specific mechanisms (a list of which exist from conceptual and analytical modeling work from the 1960's-1990's) that control Venus' circulation.

Venus as a Stress Test of GCM Cores

In a community intercomparison effort [7], we showed that even with simplified Newtonian forcing [2] different GCMs showed significant sensitivity to the implementation (in particular the diffusivity) of the numerical foundation (core) of the GCMs.

Early tests with the PlanetWRF GCM developed within our group, the NCAR-CAM, and the GFDL-FMS models produced similar results to [7]. Specifically, the WRF and CAM cores were found to be unsuitable for Venus GCM studies without significant modification of the GCM's numerical core. WRF suffered from errors associated with the polar filter, while CAM produced overly-damped waves that inhibited the simulated winds. WRF and CAM both perform well for Earth and Mars, and WRF (but not CAM) performs well for Titan. It is clear from this work that some Earth climate models need significant modification to perform well in the regime of slow rotation and enhanced wave activity (Titan and more so for Venus).

Ashima's FMS Venus GCM

Our Venus GCM effort has concentrated on the GFDL Flexible Modeling System (FMS) that allows almost transparent access to different GCM cores (spectral, grid point, and finite volume) that in turn allow us to study the effect of different model implementations. This reduces the likelihood of spurious attribution of dynamical errors to parameterization of physical processes (*e.g.* strong numerical diffusion behaves as a proxy for wave breaking). We initially integrated FMS with simplified forcing and examined the effects of numerical approximations independent of assumptions about physical processes [8].

To produce a GCM that more accurately simulates the Venus atmosphere we have included an increasing number of physically-based parameterizations of surface and atmospheric processes. A thermal-flux balance model determines the surface and sub-soil temperature, boundary layer processes including topographic interactions are simulated using a non-local K parameterization [9] and convective processes are modeled using modified versions of the vertical diffusion approximations used in the FMS AM2 model.

To reproduce the thermal structure and radiative forcing in the Venus atmosphere we have developed a fully realistic and self-consistent Radiative Transfer Model (RTM) [10]. This RTM simulates solar and atmospheric fluxes over a wide spectral range and has been validated against observations of fluxes throughout and above the atmosphere [10]. In addition, the RTM produces radiative-convective temperature profiles close to reference measurements using only composition information and optical properties (figure 1).

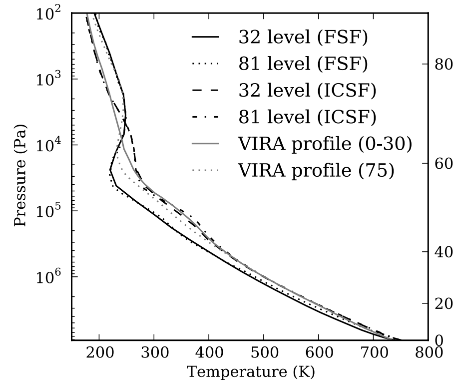

Figure 1: Radiative-convective temperature profiles predicted by the full RTM [10]. 4 cases shown, either with Internally Calculated (ICSF) or Fixed [11] (FSF) Solar Fluxes. Reference profiles from [12].

A version of this RTM using a fast KDM flux solver [13] has been incorporated into the Venus GCM, maintaining much of the flexibility of the original RTM and adding the ability to simulate advected clouds in the GCM. In the RTM we ensure the important spectral regions for *net* fluxes are properly simulated. For example we consider both solar and atmospheric fluxes in the 1-5 micron region because of its influence on the thermal structure.

GCM Simulations

Simulations using the Venus GCM produce significant equatorial winds and large scale superrotation, with peak mean winds in excess of 100 m/s (see figure 2) and show many elements of the observations. For example, the simulations have a strong sub-solar to anti-solar (SS-AS) circulation above 95km, equatorial jets below, and a near-adiabatic lower atmosphere.

Simulations with different radiative forcing conditions (including diurnally averaged forcing) show similar results to figure 2, with superrotation maintained by horizontal eddy transport of momentum. These simulations also suggest that success of the model in reproducing Venus' circulation is dependent on both the net radiative flux balances and the lower atmosphere processes. In particular, the boundary layer interactions affect the steady state circulation because of the large mass of the lower atmosphere.

Current work with this GCM is concentrated on understanding the origin of the new atmospheric features created by the more realistic forcing and further improving the parameterization of convective processes in the model. This work requires careful implementation of gravity wave drag [14,15] with Venus specific parameters. As part of this work we have created a high-resolution (1/16°) maps of topography and meter-scale slopes to provide data on topographic variability and orientation to correctly simulate the mountain drag and boundary layer interactions.

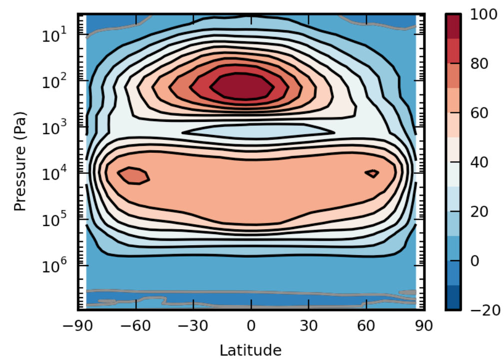

Figure 2: Zonal and time mean prograde wind, averaged over 3 sols (351 days) after 180 sol spinup.

Conclusions

We have incorporated a new fully realistic and internally consistent radiative transfer model in a state of the art Venus GCM. Simulations conducted with this new GCM reproduce the large scale superrotation observed in the Venus atmosphere. However, differences in detail remain. Ongoing work includes improving the representation of sub-grid scale effects of convection and topographic waves.

References

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