# Zonal mean structure of Venus atmosphere observed in a Venus general circulation model, DCPAM, with explicit radiative transfer calculation

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## Introduction

A unique zonal wind in Venus atmosphere, super-rotation, has been investigated by a lot of previous researchers with numerical simulations as well as observations. Among the studies with numerical simulations, Lebonnois et al. (2010) and Ikeda (2010) performed general circulation model simulations with an explicit radiative transfer model. On the other hand, we have been developing a general circulation model for planetary atmospheres. In addition, we have just developed a Venus radiation model, which can be used in a general circulation model. In this study, we try to perform general circulation model simulations of Venus atmosphere by the use of our models.

## Model description

A general circulation model used in this study is DCPAM. A Venus atmosphere radiative transfer model has been implemented in to the DCPAM.

### DCPAM

DCPAM, gfd-Dennou Club Planetary Atmospheric gcM (http://www.gfd-dennou.org/library/dcpam/), is a general circulation model for various planetary atmospheres. The model has already been used to perform experiments of the Earth, Mars, and plausible exoplanets.

- Dynamics
  - Primitive equation system
    - Spectral transform method is used to solve the equation system.
- Physics
  - Radiation
    - See below.
  - Turbulent diffusion
    - Mellor and Yamada (1982) level 2.5
    - Surface fluxes are evaluated by method by Beljaars and Holtslag (1991).
  - Surface energy budget
    - Surface and subsurface temperatures are evaluated by surface energy balance and subsurface soil diffusion equations.

### Radiation model for Venus atmosphere

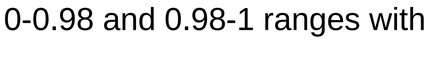
The radiation model for Venus atmosphere has been developed recently based on a k-distribution method. Absorption coefficients of Venus atmosphere used in the model was evaluated by a line-by-line model developed in our group, and reorder the absorption coefficients to construct a k-distribution table.

- Composition profile was prescribed based on following studies:
  - Crisp (1986) for $H_2O$, $CO_2$, and $SO_2$
  - Pollack et al. (1993) for CO, HF, OCS, $N_2$
  - Crisp (1986, 1989) for clouds
- Continuum absorptions were included for $H_2O$, $CO_2$, and $SO_2$.
- Band limit wavenumbers follows those of RRTMG (Iacono et al., 2008)
  - 10, 350, 500, 630, 700, 820, 980, 1080, 1180, 1390, 1480, 1800, 2080, 2250, 2380, 2600, 3250, 4000, 4650, 5150, 6150, 7700, 8050, 12850, 16000, 22650, 29000, 38000, 50000 $cm^{-1}$
- Number of bins in each band: 16
  - Two region Gaussian quadrature is used for 0-0.98 and 0.98-1 ranges with 8 bins each.
- Absorption coefficient table was constructed as follows:
  - 74 points in pressure from 0.1 to $10^8$ Pa and zero.
  - 17 points in temperature from 100 to 900 K.

## Experimental setup

Venus experiments are performed with following conditions.

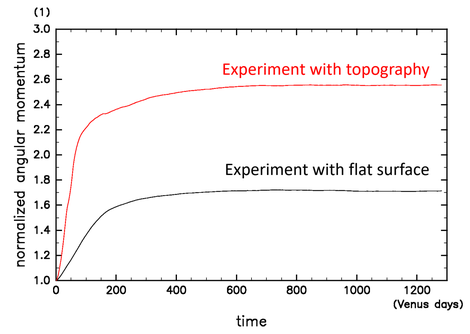
- Resolution
  - T15L52
    - 48 (longitude) × 24 (latitude)
    - 52 vertical levels
- Initial condition
  - Horizontally uniform temperature profile of VIRA (Seiff et al., 1985)
  - Zero wind velocity
- Two experiments are performed:
  - One includes a smoothed topography.
  - The other has flat surface.
- Integration period
  - 150000 Earth days
- Note:
  - Specific heat is assumed to be 900 J $kg^{-1}$ $K^{-1}$.



Topography used in an experiment.

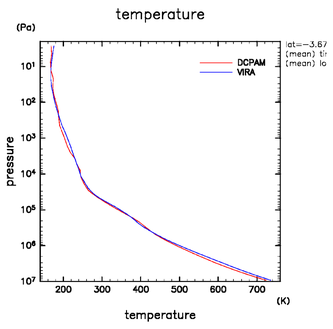
## Results of experiments

### Evolution of absolute angular momentum



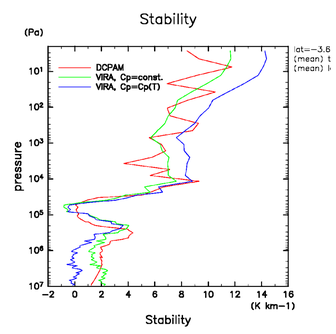
Evolution of absolute angular momentum. Angular momentum is normalized with that of atmosphere at rest.

### Temperature profile



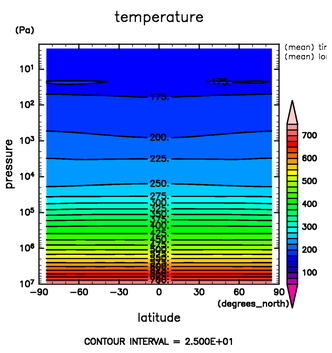
Zonal mean temperature at the equator by the model with topography (red) and temperature by VIRA (blue).

### Static stability profile

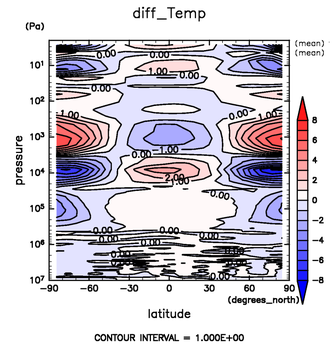


Zonal mean static stability at the equator by the model with topography(red), and static stability of VIRA (blue). Static stability of VIRA estimated with a constant specific heat (green) is also shown.

### Zonal mean temperature

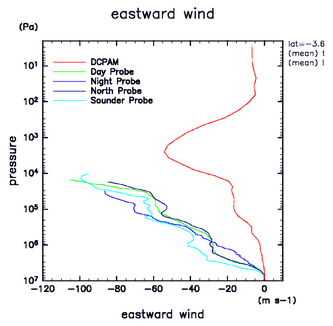


Zonal mean temperature by the model with topography

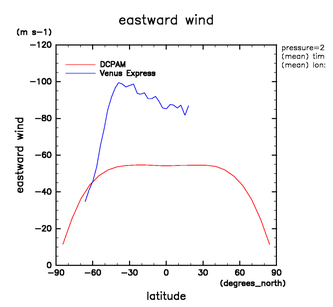


Equator to pole difference of zonal mean temperature by the model with topography

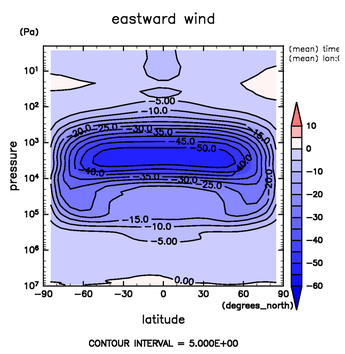
### Zonal mean zonal wind



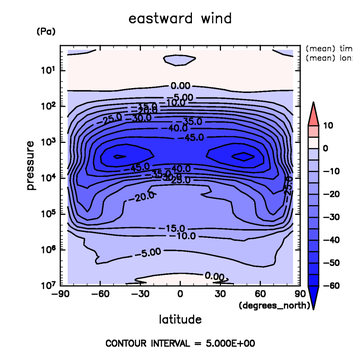
Zonal mean zonal wind at the equator by the model with topography (red) and those by Pioneer Venus probes (others) (Counselman et al., 1980).



Zonal mean zonal wind at cloud top level by the model with topography (red) and that by Venus Express (Kouyama et al., 2013).

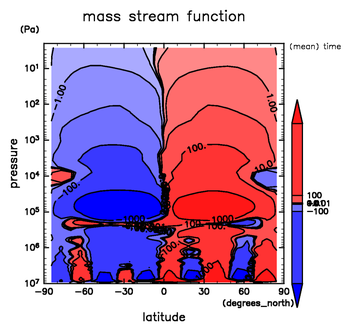


Zonal mean absolute angular momentum by the model with topography

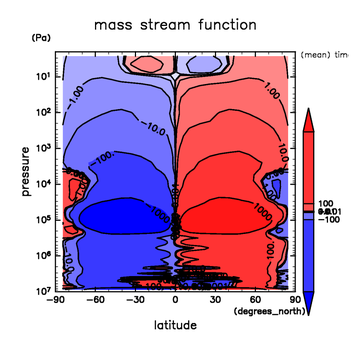


Zonal mean relative angular momentum by the model with flat surface

### Meridional circulation



Eulerian mean mass stream function by the model with topography



Eulerian mean mass stream function by the model with flat surface