Exploration of the Parameter Space for Circulation Regimes of Terrestrial Planetary Atmospheres with Simplified GCM

Y. Wang[1*] P. Read[1] J. Mendonca[1]

1. Atmospheric, Oceanic and Planetary Physics, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, UK
* Email: wang@atm.ox.ac.uk

1. Introduction

Our explorations of the terrestrial planets within the Solar System have revealed great diversity in their atmospheric circulation regimes, suggesting that a systematic study of the underlying dominating factors necessary[1]. The question we are trying to answer here is whether it is possible to predict the global circulation structures of terrestrial exoplanets, based on a limited set of planetary parameters available. With planetary rotation rate as a starting point, we began building up a multi-dimensional parameter space in which the occurences of a series of circulation regimes are mapped. This kind of parametric approach has a long tradition in the laboratory studies of differentially heated rotating fluids[2] as well as the numerical studies of the Earth's atmosphere[3]. Characterising parameters are usually in dimensionless forms, e.g. thermal Rossby number, Taylor number...

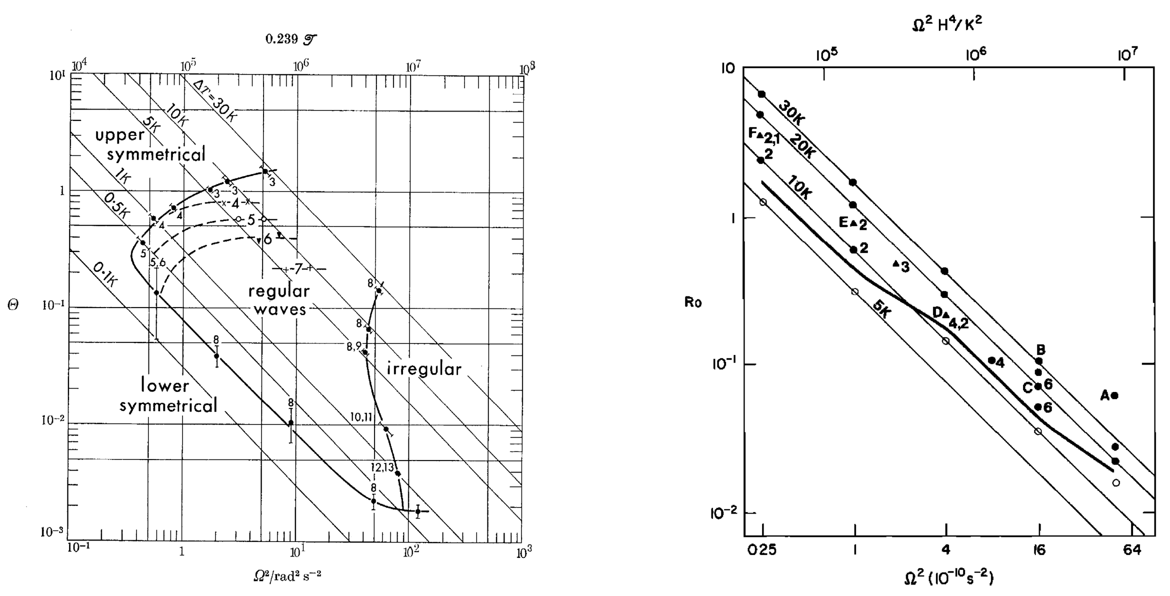

Fig. 1 Regime diagrams obtained using laboratorial rotating annulus (left, from [2]) and numerical GCM experiments(right, from [3])

We use PUMA (Portable University Model for Atmospheres) to investigate the sensitivity of planetary circulation to rotation rate. A series of controlled experiments is conducted ranging from $\Omega = 8\Omega_E$ to $\Omega = 1/16\Omega_E$.

2. Sensitivity to rotation rate

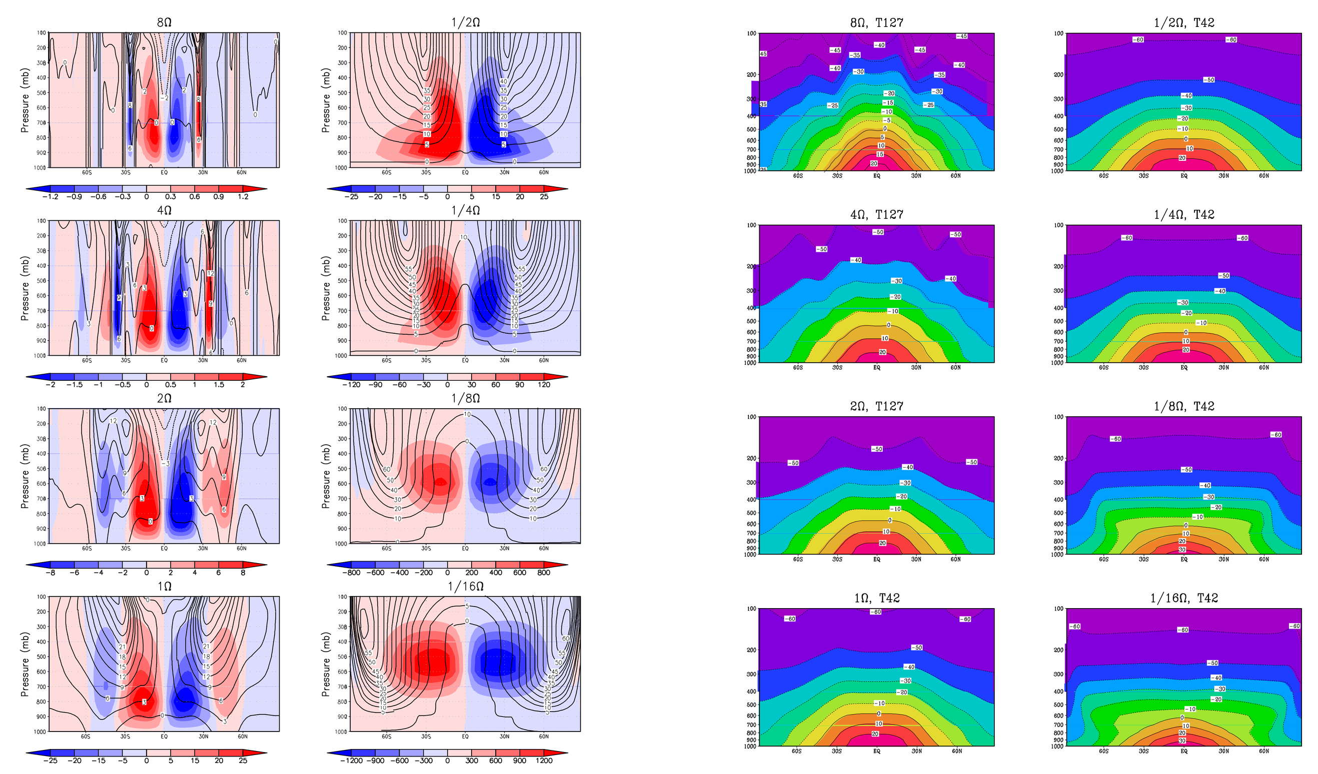

Fig. 2 Zonal and temporal mean diagnostic fields of experiments with various rotation rates. Left: zonal mean zonal wind (contour) and meridional mass streamfunction (shaded, unit 10^9 kg/s); Right: zonal mean temperature.

Multiple jet streams appear as the rotation rate increases, like what we observed on the gas giants within the Solar System. Hadley cell expands greatly as the rotation rate decreases, leading to a much smaller horizontal temperature gradient. Staircase-like features can be found in the temperature field at higher rotation rates, indicating the development of alternating eastward and westward jets and baroclinic zones.

Eddy activity is shown in the figures below. High rotation rate runs exhibit multi-band structures with broad wavenumber spectrum and small eddy scale. Low rotation rate runs show greater wave amplitude with small wavenumber (1 or 2).

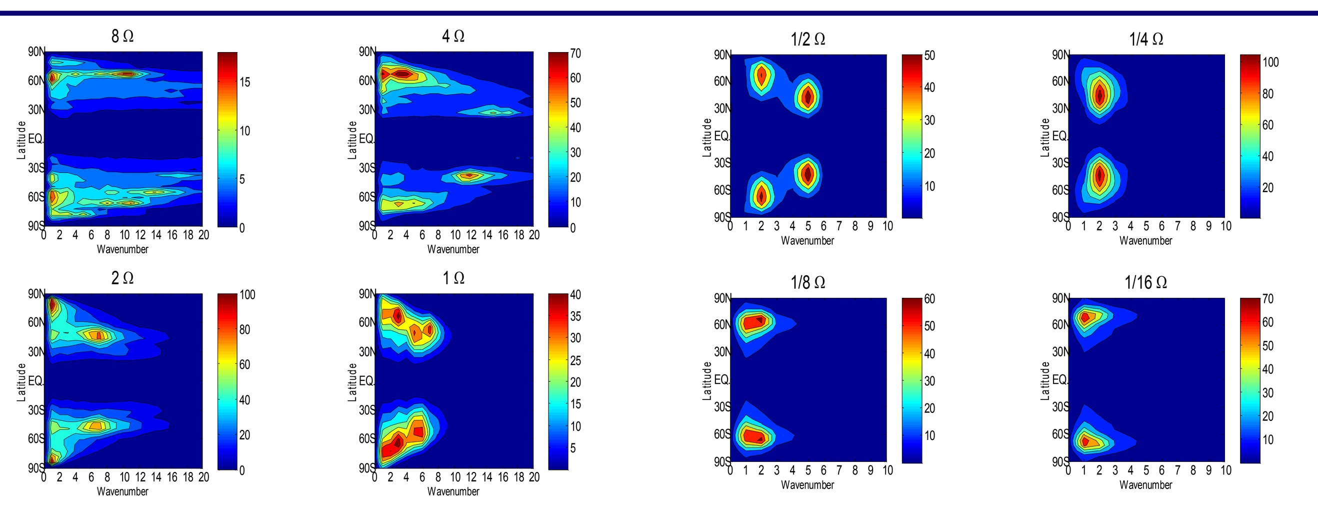

Fig. 3 FFT spectrum of the geopotential height field at 300mb. Colours represent the Fourier amplitude.

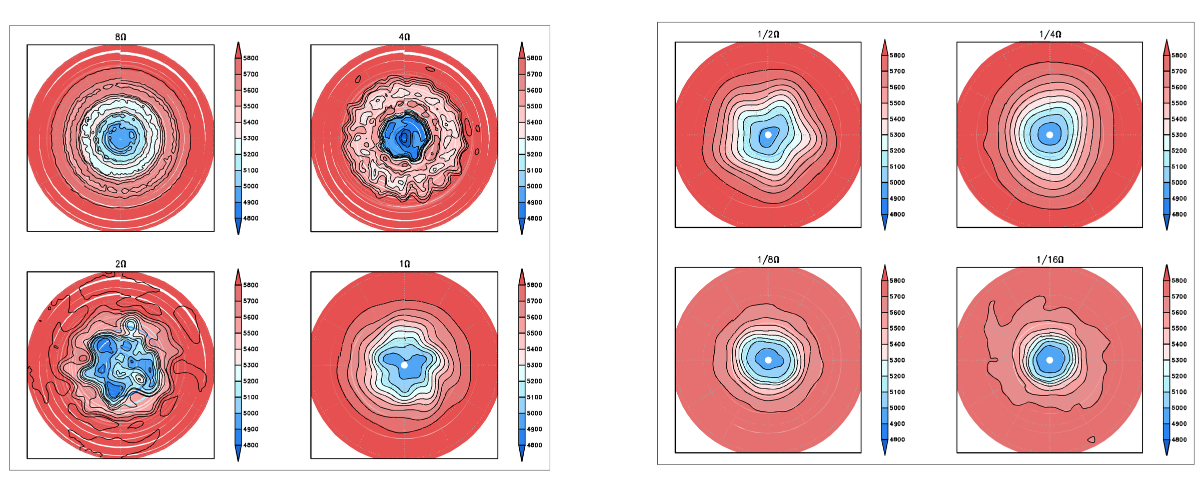

Fig. 4 Snapshots of the geopotential height at 500mb level.

3. Development of a simple radiation scheme

PUMA employs Newtonian cooling to represent the diabatic heating and cooling effects in the atmosphere. This formulation, although has an intuitive linear structure, is not based on real physics. In order to include the radiative transfer processes explicitly in the model physics, we are currently working on developing a highly simplified radiation scheme. It divides the atmospheric spectrum into two bands: longwave thermal radiation band and shortwave stellar radiation band, each with constant transmission (i.e. constant absorption coefficient). The philosophy is to represent the radiative properties of terrestrial planetary atmospheres with as few (dimensionless) parameters as possible. Potential defining parameters for this simplified radiation scheme are as following:

Ratio of optical depth between longwave and shortwave bands: $\eta = \dfrac{\tau_{lw}}{\tau_{sw}}$

The planetary albedo: A The longwave optical depth: τ_{lw}

Before incorporating this radiation scheme into the 3-D GCM, it would be instructive to first implement the radiative transfer in a 1-D column form. Here we developed a radiative-convective model to test this simplified scheme. The model is largely based on the complex radiation transfer scheme of the Oxford Venus GCM (see the poster by Mendonca et al.) with modifications to remove the specific details related to the Venus atmosphere.

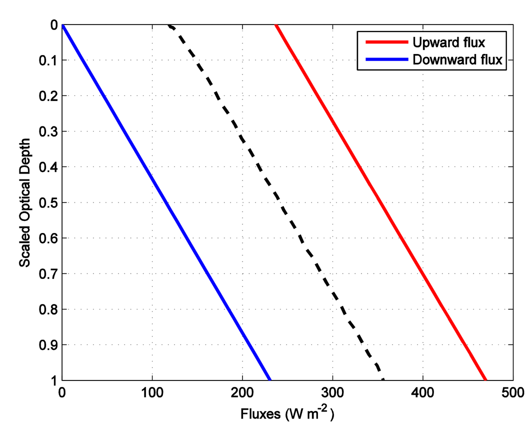

Fig.5 Model calculated fluxes at radiative equilibrium assuming zero absorption to shortwave radiation(IR grey atmosphere). Black dash line represents the radiation from the cloud.

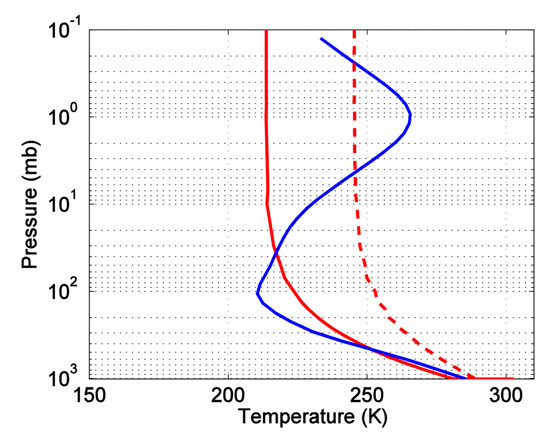

Fig.6 Comparison of temperature profiles of (a) IR grey atmosphere at radiative equilibrium(red solid), (b) two-band non-grey atmosphere at radiative equilibrium(red dash line), (c) global average of observations for the Earth

4. Future work

Work in the next stage will be to couple the radiative scheme with PUMA. Future work will also include investigating planets in tidally-locked state as well as planets of extreme obliquity.

References

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