New results from the Oxford Venus GCM

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Introduction.

The circulation of Venus's atmosphere is well known to exhibit strong super-rotation and a variety of enigmatic features which remain poorly understood. Recent work in Oxford has resulted in the development of a simplified general circulation model (GCM) of its atmosphere, which is already capable of quantitatively reproducing some aspects of its meteorology [1][2][3].

In this work we adapt and extend the existing 3D time-dependent numerical circulation of Venus's atmosphere to include a new physically-based radiative transfer formulation in the infrared. This new parameterisation is based on the net exchange approach from [5], and its accuracy is studied using a 1D configuration in the GCM. In a preliminary study of atmospheric transport on Venus, the GCM has computed and obtained diagnostics from the surface to an altitude of around 90km over complete annual and diurnal cycles, including simple representations of cloud formation and transport [3]. Amongst other features, we investigate the possible existence of a transport barrier in the atmosphere of Venus from the analysis of potential vorticity fields (PV). There is also some evidence for meridional transport to be inhibited in the Earth [6][7] and Mars's atmosphere. We studied the nature of the flow by analysing the dominant terms in the meridional component of the equation of motion.

Model.

The Venus GCM used is based on an advanced GCM for Earth [8], and it was adapted for the study of the atmosphere of Venus [3]. The Venus GCM uses values from [9] for physical properties, and simplified parameterisation for radiative forcing and boundary layer dissipation. It is configured as an Arakawa B grid [10], and adapted to use a 5x5 horizontal resolution covering the entire domain with 31 vertical levels, extending from the surface to an altitude of around 90km, with a maximum of 3.5 km for the vertical grid spacing.
The results shown in this work are obtained by integrating the model for 25000 earth days, starting from a rest state. Fig. 1 shows the westward and northward winds and temperature maps.

Radiative parameterisation in the Venus GCM.

Fast and accurate computations of the atmosphere's energy exchange via infrared radiation for long periods of integration, has been a challenging problem within the Venus GCM community. Here we adapt the Net-Exchange parameterisation of thermal IR radiative transfer in Venus's atmosphere from [4] and [5], to be eventually coupled with a short-wave radiation parameterisation based on a general 2-stream Delta-Eddington code from the the HadAm3 model [11].
The Net-Exchange Rates are evaluated from the difference in the Planck function for different layers, multiplied by an exchange factor obtained with a complete radiative transfer model (KARINE). It is assumed that the vertical distributions of IR absorbers and scatterers in the GCM are constant with time.
Fig. 2 shows the radiative budgets of the IR scheme using the VIRA temperature profile and the values that have been used to parameterise the solar heating near the equator [16]. A vertical profile of temperatures computed in 1D with convection using this new radiative scheme, is shown as well.

Atmospheric Transport Barrier.

The transport barrier is a well known phenomenon in the Earth's atmosphere (Fig. 3), and its mechanism is used to explain the isolation of the Antarctic ozone hole [12]. The study of the transport barrier in the Venus GCM was analysed using the potential vorticity (PV) barrier mechanism [13], in the regions where the PV gradient on isentropic surfaces is relatively strong and the transport barrier is formed. The evidence for this phenomenon, which appears near the westward jets in Venus, is also observed in Mars GCM (Fig. 3). In the westward jets zone, the strong gradient of the PV is associated with a large Rossby wave restoring force which inhibits meridional mixing at large scales. At small scales, the meridional shear acts to inhibit meridional mixing (Fig. 4).

Meridional study of the atmospheric dynamics.

By studying the meridional component of the equation of motion on a spherical planet of radius *a* and angular velocity *Ω*, we analysed the contributions of different terms from the model's diagnostics (Fig. 5). The aim was to elucidate the real nature of the atmosphere's zonal mean dynamics, especially at high latitudes, where cyclostrophic methods to retrieve the zonal winds seem to breakdown.

Conclusions.

. The new radiative scheme is capable of rapidly computing the energy exchange in the atmosphere. This simple parameterisation makes uses of the output of a full radiative transfer model, which gives a more realistic picture of the energy exchange in the atmosphere than the newtonian cooling approach.

. The transport barrier that is evident in Mars and in the Earth, has an important role in the dynamics of the Venus atmosphere in determining the distribution of the clouds. Near the jets, meridional tracer transport is inhibited and forms a barrier that follows the dynamics of the waves.

. At the altitudes analysed, the results show that the equation of motion is dominated mainly by three terms: the centrifugal acceleration, the geopotential gradient and the residual. The residual in Fig. 5 is most probably due to the variability of the flow with time, and seems to be related to the turbulent zone near the jets dominated by eddy momentum fluxes. These quantities seem to be important in the Polar regions near the jets, leading to a breakdown of the cyclostrophic approximation.

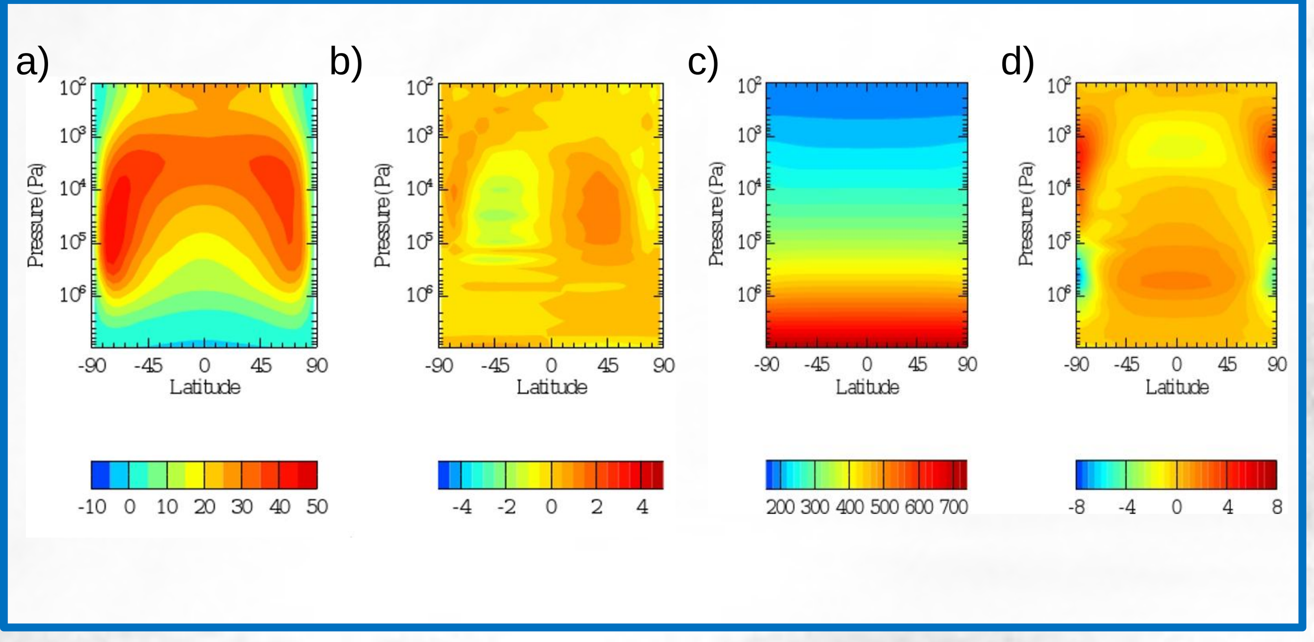


Figure 1.
Standard diagnostics of the Oxford VGCM from [3](without the diurnal forcing).
a) Westward wind speed (m/s)
b) Northward wind speed (m/s)
c) Temperature(K)
d) Temperature after the latitude mean has been removed (K).

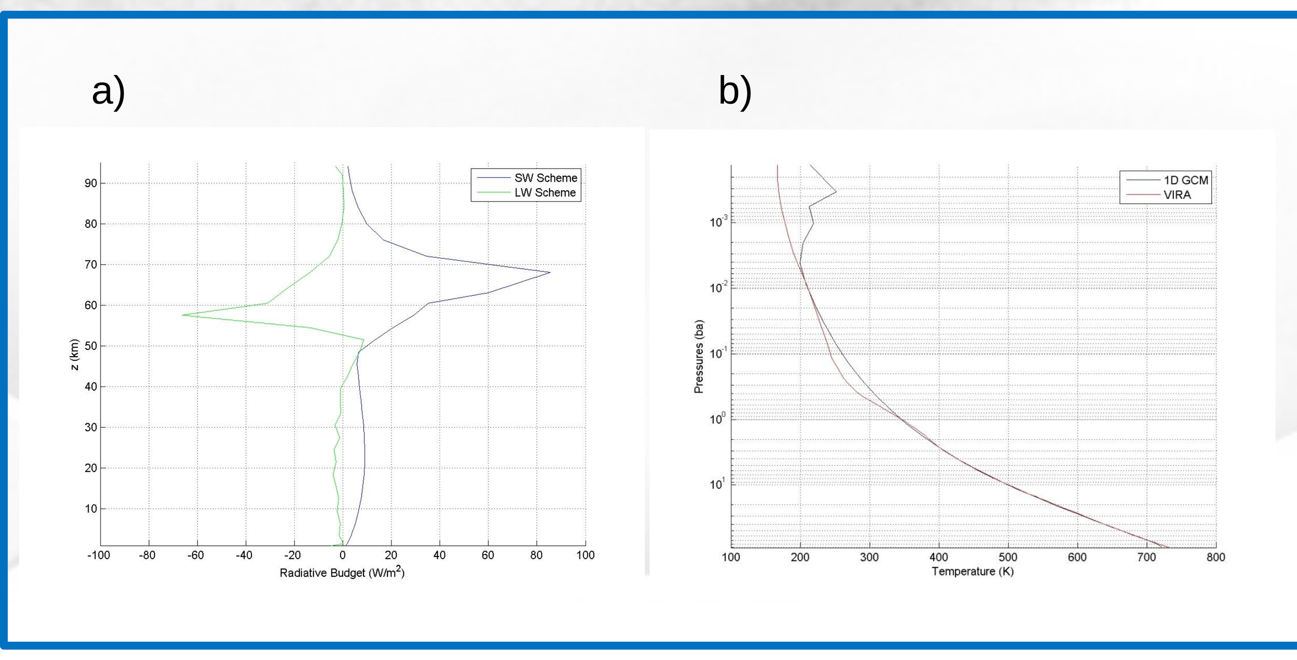


Figure 2.
a) The contribution of radiative budget (W/m²) to the heating rate as function of altitude.

b) Temperature profile after 12000 Earth days of integration in 1D with convection. The profile VIRA is from the "Venus International Reference Atmosphere", which was used as the initial conditions.

Note: The values of the temperature profile were averaged over the last 50 Earth's days.

SW – Short-Waves
LW – Long-Waves

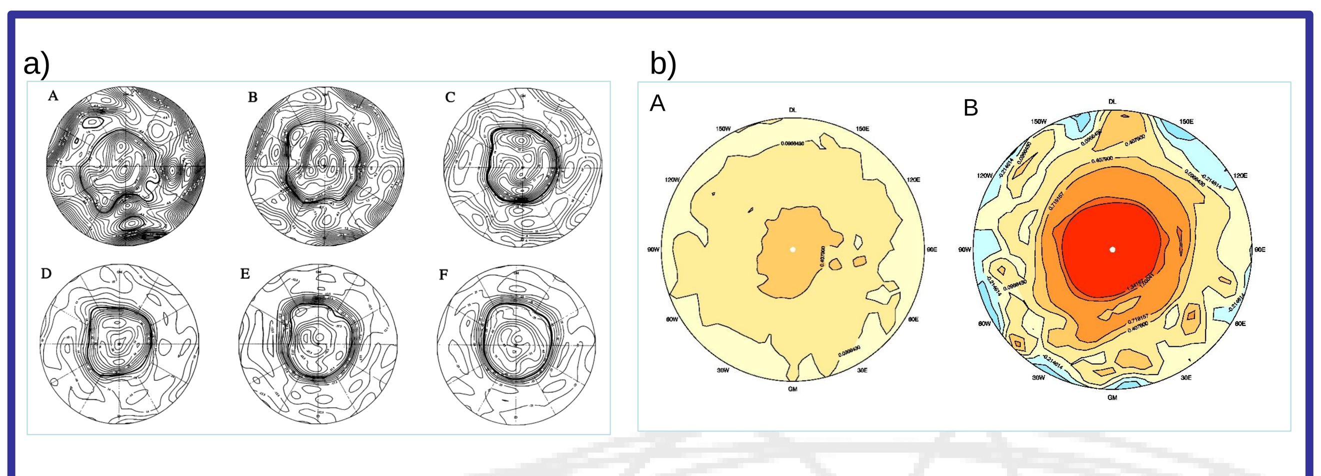


Figure 3.
These figures show some examples of the evidence of a mixing barrier which has been observed in the Earth [13] a) and Mars's b) atmosphere. a) is on the isentropic surfaces: (A)350K, (B) 375K, (C) 400K, (D) 425, (E) 450 K and (F) 500K; and the contour intervals are 0.4,1,1.5,2.5 and 5 PVU. The units in b) are in 100PVU and is on the isentropic surfaces: (A) 300K and (B) 500K.

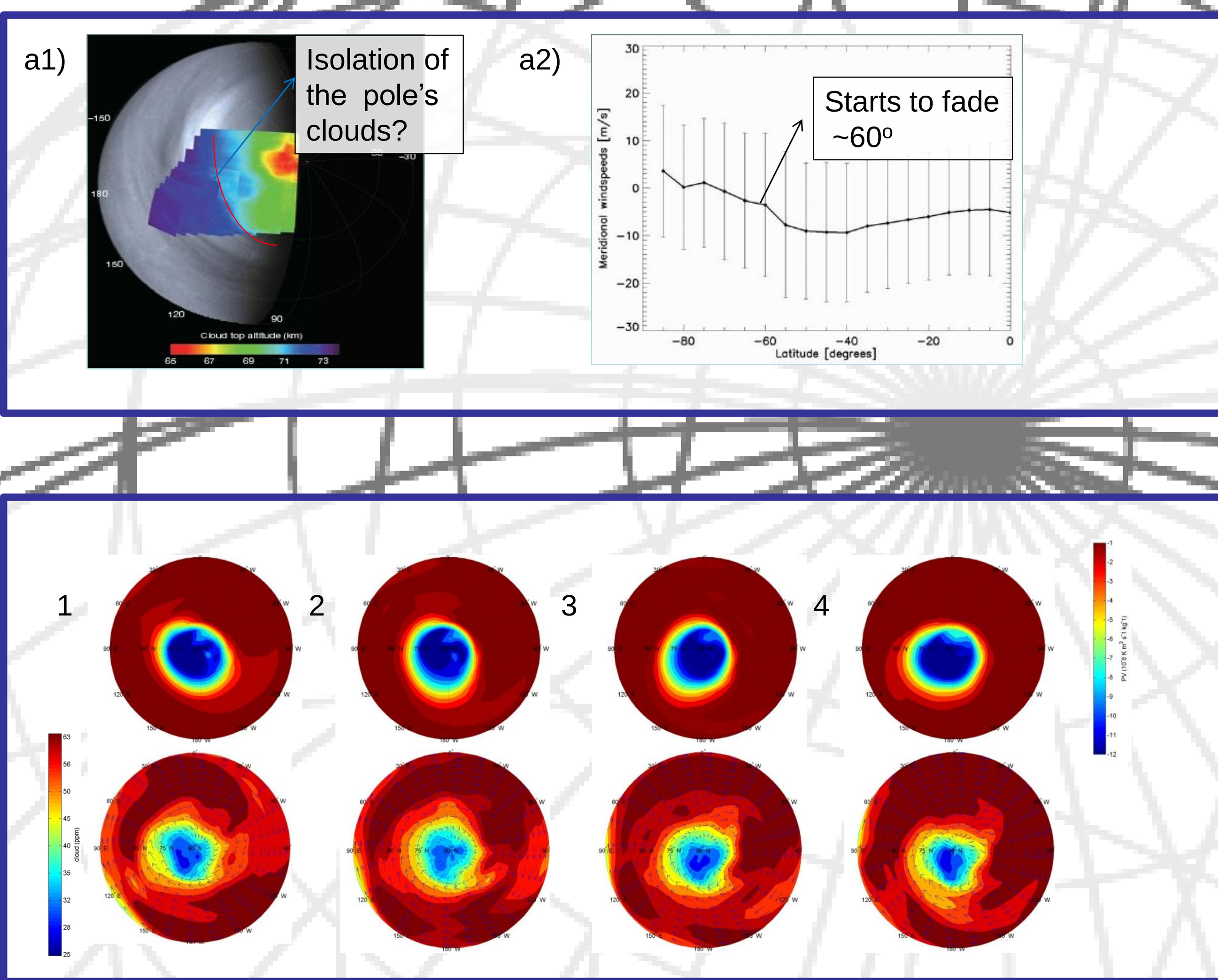
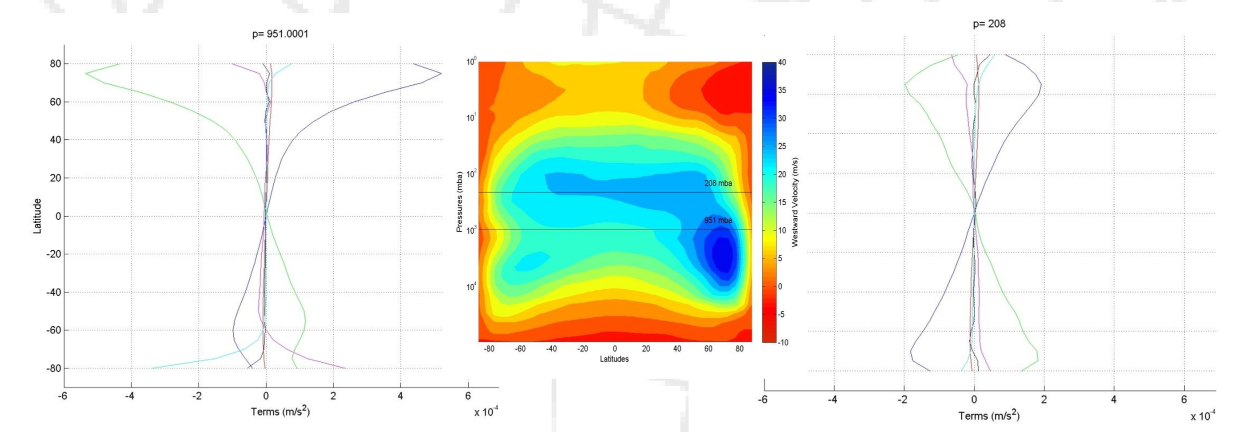


Figure 4.
Observational evidence of a transport barrier in Venus's atmosphere.
a1) Image of the clouds in the south pole of Venus [15].
a2) The meridional component of the winds [16].

Results from the model.
b) PV field on an isentropic surface (864K) and the horizontal cloud distribution on a pressure surface (951hPa) which corresponds roughly to the same altitude in the atmosphere, with one day of interval between each image.
Note:
1hPa = 1mba
PV units used: 10^{-8} K m^2 s^{-1} kg^{-1}
Cloud units used: ppm



$$Residual + \frac{\bar{u}^2 \tan\theta}{a} + \bar{u}2\Omega\sin\theta = -\frac{1}{a}\frac{\partial\bar{\Phi}}{\partial\theta} - (a\cos\theta)^2 (\overline{v'^2}\cos\theta)_\theta - \overline{u'^2} a^{-1}\tan\theta$$

Two of the main eddy terms

Figure 5.
The different colours represent each term of the meridional component of the equation of motion. They were obtained after 40000 earth days in the GCM integration without diurnal forcing, and afterwards over 150 days with diurnal forcing. Each variable *v*, *w*, *u* and *Φ*, was averaged over longitude and over time (40 days).

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