Planetary and atmospheric properties leading to strong super-rotation in terrestrial atmospheres

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Background

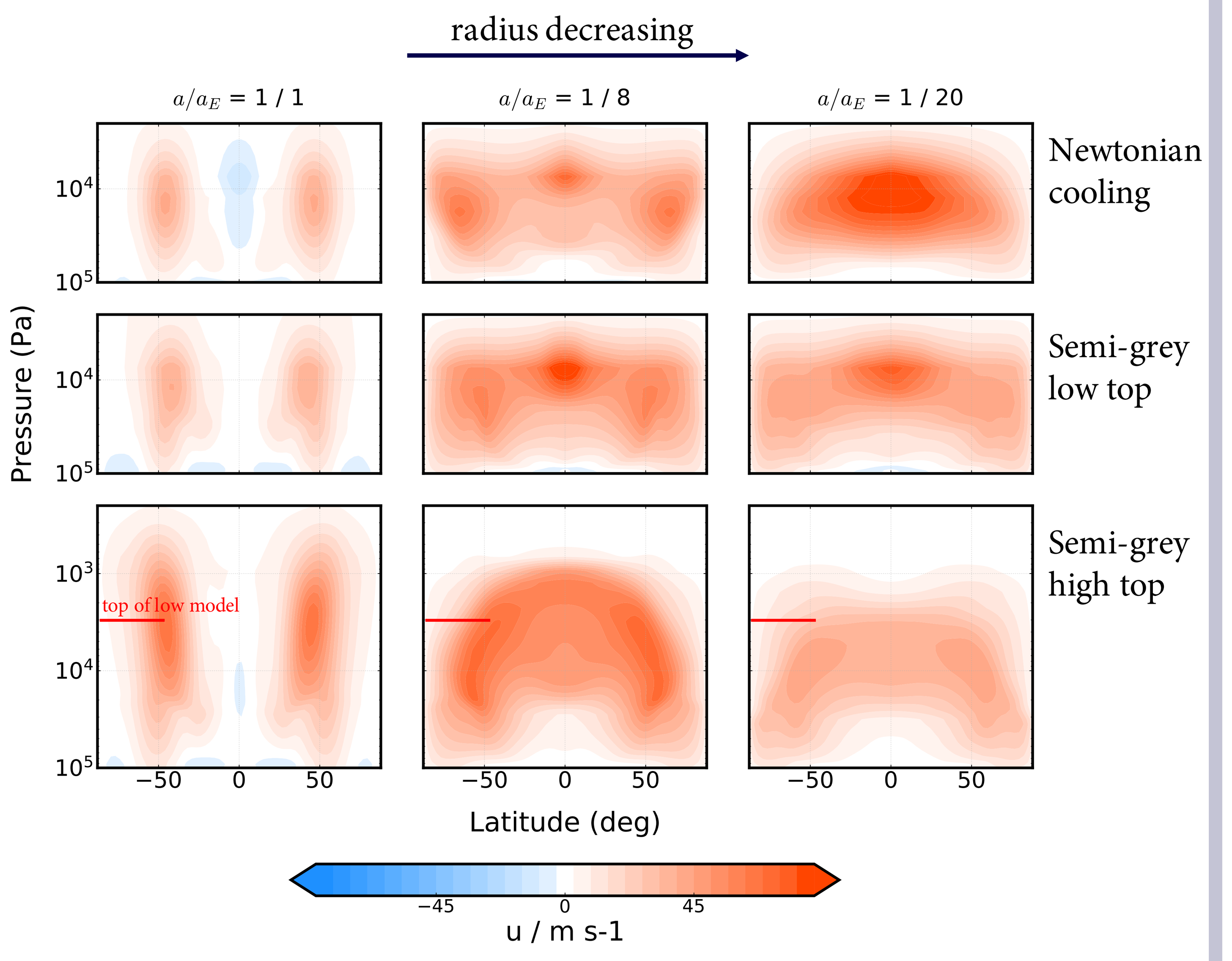
Super-rotation is a phenomenon where the specific axial angular momentum of the wind exceeds that of the underlying planet at the equator [1]. Non-axisymmetric disturbances (eddies) are required to accelerate a super-rotating zonal flow [2]. Super-rotation is a permanent feature of the atmospheres of Venus and Titan, but not the Earth and Mars [1]. This raises a question as to the origin and nature of the eddies that induce the required momentum transport.

Previous work using idealised dry general circulation models (GCM) with simplified physics (Newtonian cooling, linear surface friction) has shown that super-rotation may emerge 'spontaneously' on planets that are small or slowly rotating [3-5]. This transition to super-rotation may be relevant to Titan (and potentially Venus) [6]. However the strength of super-rotation obtained in studies of this type is far weaker than that observed in Venus' or Titan's atmospheres, or in numerical models of either planet.

Aim

Our aim is to take a step towards 'reality', by studying the transition to super-rotation in a GCM with parametrisations that are more sophisticated than those used in previous idealised modelling studies [3-5], but still simplified when compared to models tuned to simulate a specific planet (e.g., refs. 7 and 8 for Venus, or ref. 9 for Titan). We use our simulations to investigate how properties of Venus and Titan (e.g. slow rotation rate, small radius, large atmospheric mass, absorption of solar radiation in atmosphere) may combine to yield strong super-rotation. **The results in this poster are a preliminary 'sneak peak' of our results. More to come soon!**

Comparison between 'semi-grey' and Newtonian cooling models



Aim: explore the effect of reducing planetary radius on the transition to super-rotation. The experiments compare the circulation obtained in Newtonian cooling (NC) vs. semi-grey (SG) models, and models with a high top vs. a low top.

The transition occurs in all configurations of our model when radius is reduced. However, there are differences between the semi-grey and Newtonian cooling approaches, and high and low top models.

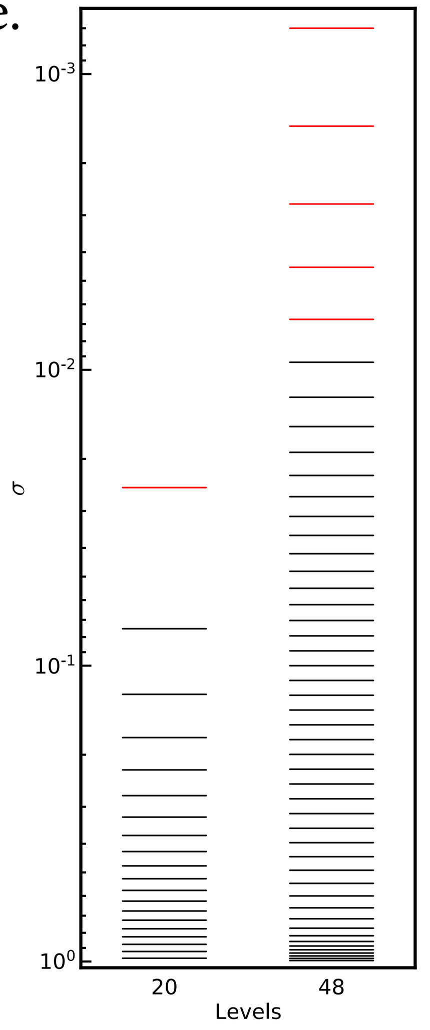
For the NC model, super-rotation strength increases monotonically with decreasing radius. For the SG model, super-rotation is strongest for $a/a_E = 1/8$.

Zonal velocity structure is similar for both low top configurations (top two rows), but different for the high top model. In this scenario, the circulation extends to fill the stratosphere.

Model

Our 'semi-grey' model is built using Isca [10], which is a flexible framework for modelling the dynamics of planetary atmospheres built on the GFDL spectral core.

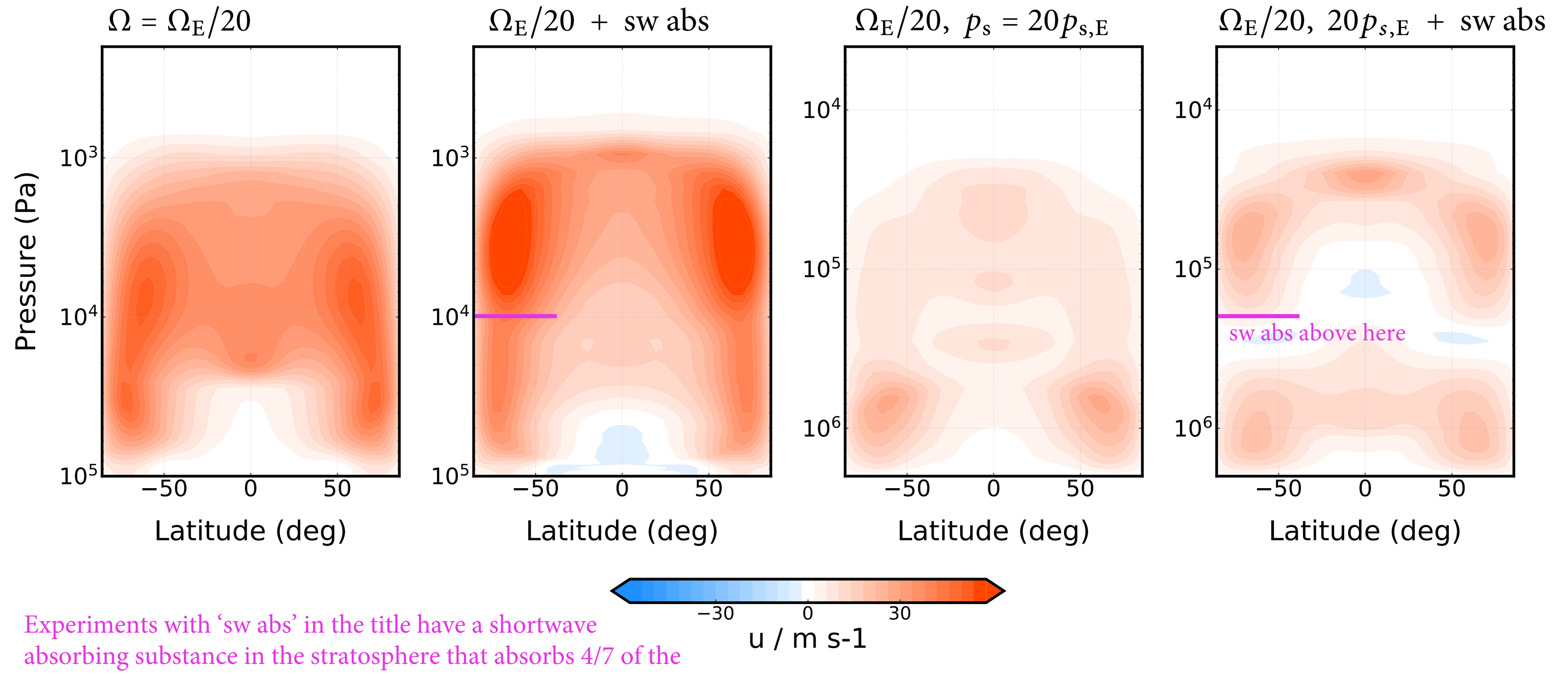
We run simulations at T42 (~2.5°) resolution. Two configurations are used for the vertical resolution, one 'high top' and the other 'low top' (for comparison with ref. 3). These are shown on the right. A sponge is included at the top (red levels).



Radiative transfer is handled with a semi-grey code with fluxes split into 'longwave' (thermal) and 'shortwave' (solar) bands.

Boundary layer turbulence and the effects of surface friction are parametrised with a diffusive boundary layer code.

Effects of surface pressure, rotation rate, and shortwave absorption



Experiments with 'sw abs' in the title have a shortwave absorbing substance in the stratosphere that absorbs 4/7 of the incoming solar radiation (fraction chosen to match Titan).

Aim: explore the effect of rotation rate, p_s, and stratospheric absorption of shortwave radiation on super-rotation.

Super-rotation is weaker compared with reduced radius experiments (note different colour scale). This is due to the enhanced effects of surface friction and thermal forcing when rotation rate is reduced [11].

Increased p_s appears to weaken super-rotation. This is not yet understood, and the simulation may not be fully equilibrated.

When a stratospheric shortwave absorber is included, super-rotation is enhanced there. The combination of increased p_s, reduced rotation rate, and a shortwave absorber yields a Titan-like super-rotation structure.

Next steps…

Analyse similarities and differences between waves accelerating super-rotation in reduced radius experiments across different model configurations.

Understand the role of model top location in setting the lower stratospheric and tropospheric circulation.

Extend the rotation rate, surface pressure and shortwave absorption study to a full parameter survey to see how super-rotation scales with each of these.

Investigate the role of diurnal tides in accelerating super-rotation for different parameter combinations, and the relation between planets with a long solar day and tidally locked planets.

[1] Read and Lebonnois, 2018, Ann. Rev. EPS; [2] Hide, 1969, J. Atmos. Sci.; [3] Mitchell and Vallis, 2010, J. Geophys. Res.; [4] Potter et al., 2014, J. Atmos. Sci; [5] Wang et al., 2018, Q. J. R. Meteorol. Soc.; [6] Imamura et al., 2020, Space Sci. Rev.; [7] Mendonça and Read, 2016, Planet. Space. Sci.; [8] Lebonnois et al., 2010, J. Geophys. Res.; [9] Lebonnois et al., 2012, Icarus; [10] Vallis et al., 2018, Geosci. Model. Dev.; [11] Dias-Pinto and Mitchell, 2015, Icarus.