SUPER-ROTATING JETS IN THE ATMOSPHERES OF TERRESTRIAL PLANETS. S. R. Lewis[1], J. Dawson[1], P. L. Read[2], J. Mendonça[2], T. Ruan[2], and L. Montabone[2,3], [1]Department of Physical Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK (s.r.lewis@open.ac.uk), [2]Atmospheric, Oceanic and Planetary Physics, University of Oxford, Oxford, OX1 3PU, UK, [3]Université Paris VI, Laboratoire de Météorologie Dynamique - Tour 45-55, case courrier 99 – 4, place Jussieu, Paris, France.

Introduction: Super-rotation is a ubiquitous phenomenon in the four substantial atmospheres possessed by solid bodies in the solar system. The slowly rotating planet, Venus, and moon, Titan, are both well-known to have atmospheres that rotate substantially more quickly than does the solid surface underneath. The more rapidly rotating planets, Mars and Earth, exhibit less spectacular global super-rotation, but both provide examples of prograde jets near the equator which rotate more rapidly than the equatorial surface. It is also worth noting in passing that atmospheric super-rotation is not restricted to planets with solid surfaces and shallow atmospheres, but that Jupiter and Saturn both possess rapid prograde equatorial jets [e.g. 1] and hence exhibit local super-rotation.

In each case the detailed mechanism, or combination of mechanisms, which produces the super-rotating jets might vary, but all require longitudinally asymmetric motions, waves or eddies, to transport angular momentum up-gradient into the jets. This paper will review recent global circulation model results and, in the case of Mars and Earth, atmospheric reanalyses by data assimilation, in order to diagnose possible mechanisms in each case.

Measures of super-rotation: For comparative purposes it is useful to introduce measures of local and global super-rotation [2, 3]. Local super-rotation, s, is defined as the ratio of the angular momentum of the atmosphere about the rotation axis of the planet to the angular momentum of air at rest relative to the surface at the equator minus one. Global super-rotation, S, is the ratio of the total atmospheric angular momentum of the atmosphere about the rotation axis of the planet to the total angular momentum of an equivalent atmosphere in solid-body rotation with the planet, again minus one. In both cases, positive values indicate super-rotation compared to that which might be achieved by rearranging an atmosphere initially at rest only by axisymmetric processes [4].

Mars and Earth: The Earth exhibits a small positive global super-rotation with S = 1–2% [2], and relatively weak local super-rotation can also be observed, particularly in the westerly phase of the Quasi-Biennial Oscillation (QBO); a prograde wind u = 20 m/s at the equator on Earth is equivalent to a local super-rotation of s = 4%.

Modelling studies [3] using the UK (spectral dynamics with angular momentum conservation enforced) version of the LMD-UK Mars Global Circulation Model (MGCM) [5, 6], as well as results from earlier studies [7], demonstrate that Mars might exhibit stronger super-rotation, with S = 4–6% and s = 8–16% depending on the dust loading and time of year [3]. See also Fig. 1 here.

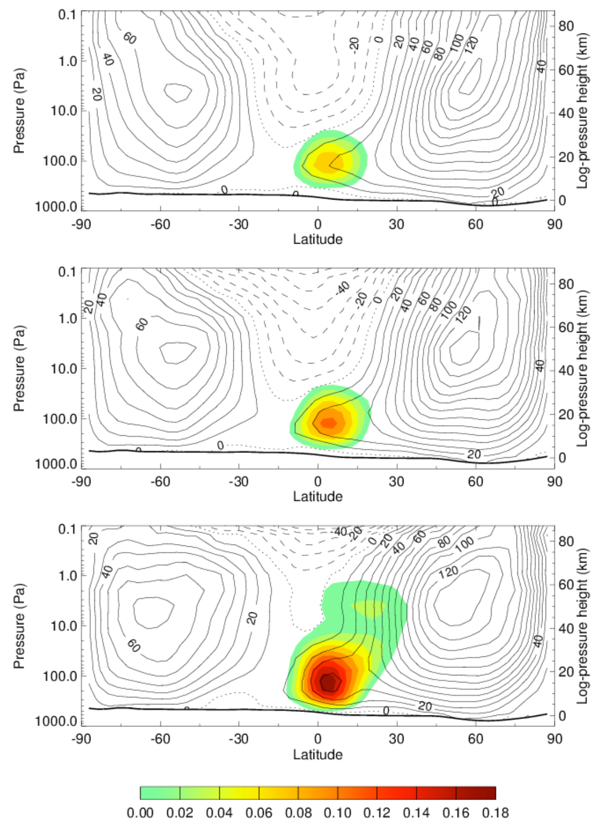

Figure 1: Zonal wind (contours) and local super-rotation index (colours) at northern hemisphere autumn equinox (L_S = 180°) in the UK MGCM [3]. Only positive values of s are shaded to highlight regions of super-rotation. The dust optical depth is varied from moderate to levels approaching planet-encircling dust storms, such as the L_S = 185° event in 2001 ($\tau_{610\mathrm{Pa}}$ = 0.6, 1.2 and 3.0 in the panels from top to bottom).

Data assimilation for Mars [8, 9] now means that the atmospheric super-rotation can be diagnosed from a re-analysis spanning almost six complete martian years covering the period for which thermal and dust observations are available from the Thermal Emission Spectrometer on Mars Global Surveyor and the Mars Climate Sounder on Mars Reconnaissance Orbiter.

Venus and Titan: The slowly-rotating bodies are the most remarkable cases of super-rotation in the solar system, with $s > 60$, $S \sim 10$ for Venus. Such large values of S are consistent with a scaling analysis using a global Rossby number [2] derived from the broadly similar wind speeds to those seen on Earth and Mars, the similar planetary radii and the much slower planetary rotation rate. Recent global circulation models have produced super-rotation for both Venus [10, 11, 12, 13, 14 and references therein] and Titan [15, 16], but results are highly dependent on the model resolution, initial state, parameterizations used and even the dynamical core.

Results will be shown from both a finite difference model primarily developed in Oxford [11, 17], which features more complete physical parameterizations, and a model run that shares the spectral dynamical core of the UK MGCM, run at The Open University [14], and see Fig. 2. A more complete international intercomparison will be presented in [18].

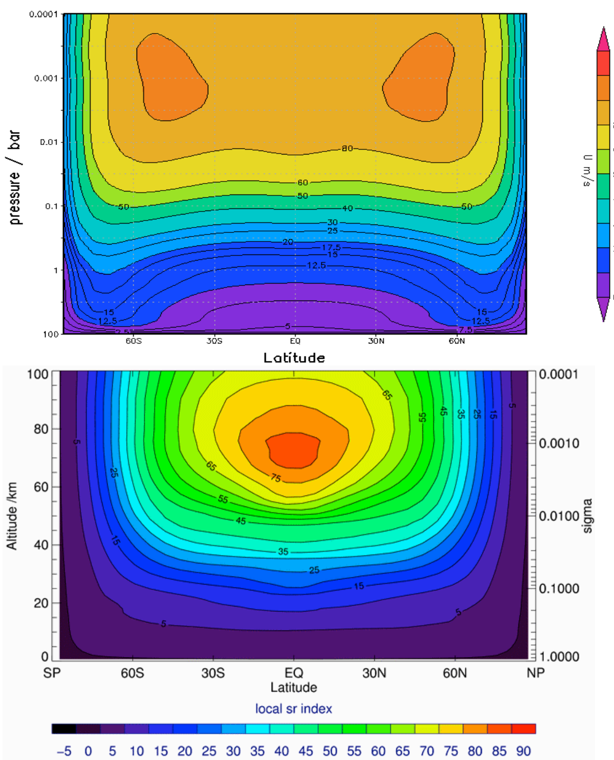

Figure 2: Upper panel: longitudinal-mean wind in the OU VGCM after 250 Venus sidereal days (about 60,750 Earth days) of spin-up from rest. Positive values indicate prograde motion. Lower panel: local super-rotation index, s, derived from the winds shown in the upper panel.

Conclusions: Local and global super-rotation require the transfer of angular momentum up-gradient with respect to the longitudinal-mean gradient of angular momentum. This transfer must be accomplished by eddy processes, which might include thermal tides, large-scale Kelvin or Rossby waves or small-scale inertio-gravity waves or even turbulent diffusive processes. On Earth especially, strong tropical convection will tend to mix angular momentum and to suppress the development of clear, local super-rotating jets in the troposphere; without the latent heat resulting from the condensation of large quantities of water, this process might be less important on other planets. Models permit the investigation and quantification of the mechanisms behind atmospheric super-rotation, for example [3] demonstrates that the thermal tides are the most important mechanism behind the formation of the low-level equatorial jets seen in Fig. 1, although an almost exactly equal global super-rotation will occur, with jets peaking elsewhere in the model if the thermal tides are artificially suppressed. The development of data assimilation techniques for other planets now permits the analysis of super-rotation in less highly idealized cases using an atmospheric reanalysis as would be done for the Earth.

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