The dependence of global and local metrics of super-rotation on planetary rotation rate

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Super-rotation is a phenomenon in atmospheric dynamics where the axial angular momentum of an atmosphere in some way exceeds that of the underlying planet. In this presentation, we will discuss the dependency of both globally-integrated, and local metrics of super-rotation on planetary rotation rate, revealed through analysis of idealised General Circulation Model experiments. The model used here is based on the Held-Suarez benchmark for a dry, 'Earth-like' atmosphere, and results from both axisymmetric and three-dimensional experiments will be presented. Previous work has shown that the three-dimensional configuration used here will transition to a state of equatorial super-rotation if the rotation rate is reduced sufficiently from the Earth's. This motivates the question: How does super-rotation strength depend on rotation rate?

We will use the term 'global super-rotation' to refer to an atmosphere with excess of globally-integrated axial angular momentum relative to that achieved by solid body co-rotation with the underlying planet, and 'local super-rotation' to refer to the existence of some region within the atmosphere where axial angular momentum exceeds that of the underlying planet at the equator. In an inviscid, axisymmetric atmosphere, the axial component of specific angular momentum is materially conserved. Consequently, in such a system local super-rotation is forbidden, although global super-rotation may still be achieved if a meridional circulation is able to transport fluid equilibrated with the equatorial surface poleward. If the restriction of axisymmetry is lifted, then local super-rotation may exist if non-axisymmetric disturbances that act to transport angular momentum up-gradient are present. The atmospheres of Venus, the Earth, Mars, and Titan may be considered to be globally super-rotating, however only Venus and Titan exhibit permanent local super-rotation at the equator.

The results from axisymmetric experiments reveal that at high rotation rate (e.g., greater than 1/4 of the Earth's), the degree of global super-rotation scales inversely with the square of the rotation rate. In the low rotation rate limit, the degree of global super-rotation saturates, and becomes independent of rotation rate. We will show that the high, and low rotation rate dependencies can
be predicted by a single analytic scaling for global super-rotation. Our three-dimensional experiments exhibit the same scaling behaviour for global super-rotation as observed in the axisymmetric experiments. The degree of global super-rotation achieved by the three-dimensional experiments is less than that of the axisymmetric experiments at high rotation rates, and greater at lower rotation rates, but in both limits the deviation from the axisymmetric 'base circulation' is small. In the low-rotation rate limit, local super-rotation is accelerated at the equator, which is consistent with the three-dimensional experiments obtaining a higher degree of global super-rotation than their axisymmetric counterparts. Estimates for global super-rotation strength on the Earth and Mars agree closely with the results of our three-dimensional numerical experiments, but Venus and Titan achieve substantially stronger global, and local super-rotation than found here. It appears that low rotation rate alone cannot induce substantial excess global super-rotation, relative to the axisymmetric base circulation we identify.