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Simulation of Titan's atmosphere with a quasi-hydrostatic GCM: relevance of the wind-induced equatorial bulge

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Abstract

The centrifugal force associated with the super-rotation causes an equatorial bulge in the middle atmospheres of Titan. General circulation models (GCMs) based on the hydrostatic primitive equations cannot correctly represent the wind-induced portion of the equatorial bulge since the vertical component of the centrifugal force does not appear in the hydrostatic equation. Consequently, these models systematically underestimate the meridional pressure gradient force and super-rotation in gradient wind balance. A Titan GCM based on the quasi-hydrostatic equations can represent the wind-induced equatorial bulge self-consistently and is shown to predict faster super-rotation than a hydrostatic GCM run under otherwise identical conditions.

1. Introduction

Most general circulation models (GCMs) of Titan's atmosphere are based on the hydrostatic primitive equations. Several of them have difficulties in reproducing the observed stratospheric super-rotation under realistic diabatic forcing patterns. Previous studies indicated that numerical inaccuracies of the dynamical core or inappropriate representation of subgrid-scale processes may have a negative impact on the maintenance of stratospheric super-rotation. On the other hand, the correctness of the primitive equations under Titan's conditions has not been seriously questioned. The purpose of this paper is to show how the primitive equations fail to represent one important feature of Titan's atmosphere, i.e. the equatorial bulge caused by super-rotation. The paper also suggests possible solutions of this intrinsic problem.

2. Wind-induced equatorial bulge

The most important feature of the primitive equations used in hydrostatic GCMs is the replacement of the vertical momentum equation by the hydrostatic equation. This approximation is problematic for Titan's atmosphere since the strong super-rotation causes a non-negligible vertical component of the centrifugal force, which does not appear in the hydrostatic equation or anywhere in the primitive equations. The centrifugal force associated with the zonal wind causes an equatorial bulge in that the pressure level in the middle atmosphere is pushed in the direction perpendicular to the planetary spin axis. The equatorial bulge is observationally evidenced by stellar occultation experiments [1,2].

This equatorial pressure bulge gives rise to much of the poleward pressure gradient force, which balances the equatorward centrifugal force to maintain the super-rotation in gradient wind balance. Since the hydrostatic primitive equations cannot represent the wind-induced equatorial bulge self-consistently, the poleward pressure gradient force is likely to be underestimated in hydrostatic Titan GCMs to a substantial degree. This in turn implies underestimation of the zonal wind speed in gradient wind balance and may be one major reason for the weakness of the predicted super-rotation in several Titan GCMs.

This shortcoming can be avoided in a non-hydrostatic GCM or a quasi-hydrostatic GCM [3], which mainly differs from a hydrostatic GCM by the inclusion of the vertical component of centrifugal force and Coriolis force in the hydrostatic equation. In addition, no shallow-atmosphere approximation is made, so that the horizontal momentum equations contain small metric and Coriolis terms neglected in the primitive equations. The quasi-hydrostatic equations are computationally more economic than the non-hydrostatic equations and the numerical scheme of the dynamical core need not be changed.

3. Simulation results

To show the impact of the correct representation of the equatorial bulge on the predicted meteorology the Cologne Titan GCM [4] has been run in its original hydrostatic version and new quasi-hydrostatic version. Each pair of simulation is run with and without topography after [5] and started from different initial wind profiles. In each model configuration the quasi-hydrostatic version predicts faster stratospheric zonal winds than the hydrostatic version. There is also some impact on the meridional circulation and temperature, particularly in the stratosphere.

4. Conclusions

In conclusion, Titan GCMs may encounter inherent difficulties in reproducing the observed super-rotation for the correct reason as long as the dynamical core is based on the hydrostatic primitive equations. Therefore, non-hydrostatic equations or quasi-hydrostatic equations are preferable in the case of Titan.

Acknowledgements

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