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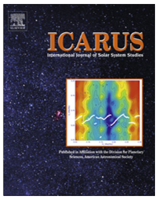

3D Modeling of interactions between Jupiter's ammonia clouds and large anticyclones

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ABSTRACT

The motions of Jupiter's tropospheric jets and vortices are made visible by its outermost clouds, which are expected to be largely composed of ammonia ice. Several groups have demonstrated that much of this dynamics can be reproduced in the vorticity fields of high-resolution models that, surprisingly, do not contain any clouds. While this reductionist approach is valuable, it has natural limitations. Here we report on numerical simulations that use the EPIC Jupiter model with a realistic ammonia-cloud microphysics module, focusing on how observable ammonia clouds interact with the Great Red Spot (GRS) and Oval BA. Maps of column-integrated ammonia-cloud density in the model resemble visible-band images of Jupiter and potential-vorticity maps. On the other hand, vertical cross sections through the model vortices reveal considerable heterogeneity in cloud density values between pressure levels in the vicinity of large anticyclones, and interestingly, ammonia snow appears occasionally. Away from the vortices, the ammonia clouds form at the levels expected from traditional one-dimensional models, and inside the vortices, the clouds are elevated and thick, in agreement with Galileo NIMS observations. However, rather than gathering slowly into place as a result of Jupiter's weak secondary circulation, the ammonia clouds instead form high and thick inside the large anticyclones as soon as the cloud microphysics module is enabled. This suggests that any weak secondary circulation that might be present in Jupiter's anticyclones, such as may arise because of radiative damping of their temperature anomalies, may have little or no direct effect on the altitude or thickness of the ammonia clouds. Instead, clouds form at those locations because the top halves of large anticyclones must be cool for the vortex to be able to fit under the tropopause, which is a primary-circulation, thermal-wind-shear effect of the stratification, not a secondary-circulation thermal feature. A planetary-scale void of ammonia clouds persists in the model southward of -38° planetographic latitude, but may partially reflect the fact that we have not yet included a full complement of vortices, all condensable species or the underlying dry-convective forcing from Jupiter's interior.

1. Introduction

Jupiter presents some of the highest quality flow visualization of any fluid system, planetary or laboratory scale, because features in its ubiquitous cloud cover are long lasting, and because its underlying circulations are so regular—with straight-as-a-ruler east–west jets and great vortices that last for human lifetimes or longer. Thermochemical equilibrium models of Jupiter's static atmosphere (e.g. Weidenschilling and Lewis, 1973; Atreya and Wong, 2005) predict that nitrogen, sulfur and oxygen combine with hydrogen to form clouds of ammonia (NH_3), ammonium hydrosulfide (NH_4SH) and water (H_2O) at around 700 hPa (1 hPa = 1 mbar), 2000 hPa (2 bar), and 5000 hPa (5 bar), respectively. A detailed summary of the current knowledge of Jupiter's clouds and aerosols is given by West et al. (2004).

In this article, our focus is on observable phenomena and consequently we emphasize the ammonia clouds over the ammonium hydrosulfide and water clouds. We seek to identify, via numerical modeling, how the pressure, wind and temperature anomalies associated with large anticyclones, specifically Jupiter's GRS and Oval BA, alter the planet's three-dimensional (3D) ammonia clouds.

1.1. Observational constraints

Information about the 3D structure of Jupiter's clouds is retrieved via remote sensing by making judicious choices of

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observational wavelengths, for example by exploiting the fact that methane gas, with its wavelength-dependent opacity, is ubiquitous and well mixed in Jupiter's troposphere. Both narrow-bandpass maps and multi-wavelength composite images (e.g. their Fig. 4 and Fig. 13f, respectively de Pater et al., 2010) can provide constraints we can compare our model output to. Cheng et al. (2008) carry out such a multi-wavelength analysis to determine the thermal structure of the GRS and the Oval BA (a.k.a. "Little Red Spot"). Asay-Davis et al. (2009) find that the clouds associated with Jupiter's largest spots cover a larger area than the domain encircled by the high-speed collar of their azimuthal winds, much larger in the case of the Oval BA. de Pater et al. (2010) overlay these collars onto images taken at multiple wavelengths, and they analyze the vertical structure of the vortices and clouds. Using similar techniques, Wong et al. (2011) investigate the vertical structure of Oval BA before and after its reddening in 2005. Pérez-Hoyos et al. (2009) study the color change of the Oval BA and they analyze its vertical cloud structure from the observed reflectivity at various wavelengths. In this article we study ammonia cloud structure, whereas the chromophores, i.e. coloring agents, are beyond the scope of this study.

Simon-Miller et al. (2002) analyze data from Voyager IRIS and the Galileo spacecraft to determine the thermal structure and the 3D cloud structure of the GRS and its surrounding area. Fletcher et al. (2010) study space-borne and ground-based thermal infrared data to determine the horizontal and vertical thermal structure of the vortex, and find a small warm core embedded inside the larger cold core of the GRS. Our goal is to use an atmospheric model with a realistic ammonia-cloud microphysics package to begin to simulate the various observed structures mentioned above. In this study, we focus on anomalies in cloud structure, wind and temperature associated with the GRS and Oval BA.

1.2. Previous modeling

There is a history spanning several decades of nonlinear, but cloud-free, numerical simulations of Jupiter's tropospheric dynamics, both with and without a deep component (Vasavada and Showman, 2005), and models that include cloud physics are beginning to emerge. The dry-air models have employed a range of different algorithmic strategies, and do a surprisingly good job of reproducing fine-scale features seen in Jupiter's clouds. The most common surrogate for clouds in these models is potential vorticity, which is usually presented in map form near the ammonia-cloud level of 680 hPa (e.g. Legarreta and Sánchez-Lavega, 2008; García-Melendo et al., 2009; Morales-Juberías et al., 2010; Morales-Juberías and Dowling, 2013).

This cloud-free reductionist approach has been able to whittle away unnecessary processes that are not needed to explain prevailing features in Jupiter's clouds. Marcus (2004) uses this approach and he creates cloudy and cloud-free regions in his simulations where the vorticity in the model is anticyclonic and cyclonic, respectively. Li et al. (2006) model moist convection on Jupiter by parameterizing its effects in terms of a vorticity source in a quasi-geostrophic model, and find that the width and strength of developing jets depend on the details of the moist convection. These techniques reproduce observed cloud patterns fairly well, but excluding the actual clouds is a natural limitation that leaves a set of questions unanswered. What are the cloud base and cloud top levels, and do these vary spatially? Are the simulated features ammonia, ammonium-hydrosulfide or water clouds? What is the density of these clouds? How do they interact with solar insolation? To begin to answer such questions, one needs to move beyond surrogate variables and towards a full cloud-microphysics scheme.

Moving to models that have some type of explicit cloud component, Lian and Showman (2010) implement a simplistic water-cloud scheme in 3D, gas-giant spin-up experiments, in which they parameterize cloud formation by removing supersaturated vapor and reintroducing it at the bottom of the model. In their study they show that latent heating can generate the banded zonal jets on the gas giant planets similar to their observed counterparts. Their simulations result in equatorial superrotation for Jupiter and Saturn and subrotation for Uranus and Neptune.

Nakajima et al. (2000) study the moist convection on Jupiter, using a local-scale 2D model and simplified cloud microphysics for water. Their results suggest that the layers above and below the water-cloud condensation level may be dynamically and compositionally separated, with well-mixed water vapor below and inhomogeneous water vapor above. Yair et al. (1992, 1995) and Hueso and Sánchez-Lavega (2001) both employ full cloud-microphysics schemes to study the Jupiter cloud problem at the mesoscale (thunderstorm-scale) level. However, they do not account for large-scale dynamical features like jets and large vortices.

The most relevant 3D jovian cloud study we are aware of to date is the work of Zuchowski et al. (2009), in particular their Section 3.3, which is entitled "Clouds in and around large scale vortices." They simulate Jupiter's ammonia, ammonium-hydrosulfide and water clouds by adapting a simple bulk cloud scheme into their large-scale 3D simulations, with phase-changes modeled as instantaneous, and no finite-rate cloud processes included. They confirm that cloud tracking does in fact yield reliable horizontal-wind measurements for Jupiter. Our results in general are consistent with their work, except we depart on the interpretation of the role of secondary vs. primary circulation on the thick, elevated clouds seen inside large tropospheric anticyclones, as discussed below.

2. Model description

For our numerical simulations we use the EPIC atmospheric model (Dowling et al., 2006, v4.3[1]) with an active hydrological cycle for ammonia, including five interactive phases (vapor, ice cloud, liquid cloud, snow and rain) as described by Palotai and Dowling (2008). The non-trivial effects of mass loading by water vapor are included to obtain a realistic background static-stability profile (Fig. 1), but otherwise water is treated in passive mode (no phase changes or latent heating) in this investigation to keep the focus on the observable ammonia clouds.

2.1. Horizontal grid

Throughout this paper, we use east longitude and planetographic latitude, unless otherwise noted. The computational domain is an oblate-spheroidal channel spanning east longitudes 0–102.4° with periodic boundary conditions, and planetographic latitudes -47.8° to -8.8°, which is wide enough to prevent the model Great Red Spot (GRS) and Oval BA from being adversely affected by the lateral boundaries (Fig. 2). We carry out a series of runs using different horizontal-grid resolutions to determine what is needed to resolve key features, and to maintain the nonlinear integrity of the vortices during months-long integrations. This yields $\Delta(\mathrm{lon}) \times \Delta(\mathrm{lat}) = 0.4^\circ \times 0.2^\circ$, or approximately 5–8 grid points per deformation length, $L_d \approx 2000$ km, consistent with recent high-resolution, cloud-free (dry) simulations (cf. Morales-Juberías and Dowling, 2013). The resolution in terms of degrees

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[1] Distributed as open-source software and available for free download from the NASA Planetary Data System (PDS) Atmospheres Node, http://pds-atmospheres.nmsu.edu/data_and_services/software/epic/epic.htm.