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Jupiter's Great Red Spot: Fine-scale matches of model vorticity patterns to prevailing cloud patterns

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ABSTRACT

We report on a set of six new matches between fine-scale features in the vorticity field of a three-dimensional (3D), primitive-equation, finite-difference model of Jupiter's Great Red Spot that includes no clouds or cloud physics, and quasi-permanent structures in reflected visible-band images of the clouds. These add to similar success by Cho et al. (Cho, J., de la Torre Juárez, M., Ingersoll, A.P., Dritschel, D.G. [2001]. J. Geophys. Res. 106, 5099–5106), who earlier captured four characteristic features of the GRS, also reproduced here, using a 3D quasi-geostrophic, cloud-free contour-dynamics model. In that study and this, the key enabling model attribute is sufficient horizontal resolution, rather than the moist-convective and cloud-microphysics processes often required to match the patterns of clouds in terrestrial hurricanes. The only significant feature that these dry models do not capture is the episodic moist-convective plumes seen in the northwest quadrant adjacent to the GRS. We initialize with Jupiter's averaged zonal winds plus an approximately balanced, smooth 3D ellipsoidal anticyclone. The threshold horizontal grid-resolution to obtain the fine-scale matches is approximately $\Delta y/L_d \lesssim 0.15$, where $\Delta y \lesssim 300$ km is the meridional grid spacing and $L_d \sim 2000$ km the Rossby deformation length. For models with this or finer horizontal resolution, the best correspondence with observations is reached after about six vortex turnaround times from initialization (~30 Earth days), but good facsimiles of nearly all the studied features appear after only 1.5 turnaround times (~7–8 days). We conclude that in images of Jupiter, it is not accurate to associate clouds with upward motion, since these dry models reproduce the observed cloud patterns without this association, and indeed the synoptic-scale vertical motions in the model, as well as those deduced from observations, do not at all correspond to the observed cloud patterns. Instead, Jupiter's cloud-top patterns indicate the effects of local shear in the manner of passive-tracer fields. As a corollary, the water clouds on Jupiter, which lie unseen below its visible clouds, are the only ones on the planet likely to correlate with upwelling in the manner that clouds do on Earth. The next step is to extend studies such as this past the reflected visible band, for example to include the GRS's 5-μm emission bright collar, which may require the inclusion of cloud physics to enable the successful simulation of large voids.

1. Introduction

Jupiter's Great Red Spot (GRS) is the largest and oldest anticyclone in the Solar System. In 1979, the Voyager spacecraft obtained for the first time high-resolution images of the cloud-top cover of this long-lived feature, showing details in and around the GRS on scales two orders of magnitude smaller than the width of the vortex. Subsequent space-based, high-resolution observations of the GRS by the Hubble Space Telescope (1994–2008), and the Galileo (1995–2003), Cassini (2000) and New Horizons (2007) spacecrafts, have provided arguably the best visualization of any geophysical vortex on any planet, including Earth. Many groups have successfully modeled a long-lived anticyclone like the GRS under a variety of conditions (see the reviews by Marcus, 1993; Dowling, 1995; Ingersoll et al., 2007; Vasavada and Showman, 2005, and references therein). The next step is to isolate what is required, and just as importantly what is not required, to capture higher-order details that are observed inside and adjacent to the GRS.

Williams (1997) used a dry, 3D primitive-equation Jupiter model to study vortex genesis and evolution related to the GRS. With horizontal resolutions of ~1000 and ~2000 km in latitude and longitude, respectively, he generated vortices with a high-velocity ring surrounding a more quiescent region in the interior of the spot, a key feature of the GRS. As cited above, Cho et al. (2001) reproduced this high-velocity ring and three additional details of the GRS using a dry, 3D quasi-geostrophic, contour-dynamics

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model (developed by Dritschel and Ambaum, 1997). Significantly, they showed that these matches are not sensitive to the precise vertical stratification. In this study, we use a dry version of the 3D primitive-equation, finite-difference EPIC model (Dowling et al., 1998) to capture these and an additional six details.

For Earth there is not yet a complete understanding of the association between atmospheric circulation regimes and the cloudiness that characterizes these weather regimes (Stephens, 2005). High clouds in Earth's upper troposphere correlate with vertical velocity mainly in regions affected by strong convection, where active cloud production takes place on short timescales close to where clouds are observed (Zhang, 2003), and cloud-free regions often indicate subsidence. Neptune also exhibits at least one type of correlation between vertical velocity and cloud formation, in the form of orographic-style bright companions to anticyclones (Stratman et al., 2001). The origin and occurrence of the high ammonia ice clouds on Jupiter is not that well understood (Atreya et al., 2005), but the apparent rarity of spectrally identified fresh ammonia ice clouds (Baines et al., 2002) suggests that once formed, ammonia ice cloud particles are relatively long-lived and persist for long times and distances from their point of origin. The cumulus-convection element of the vertical motion of Earth's clouds is powered by the strong enthalpy of vaporization (latent heat) of water. Quite unlike the cloud processes that are typically required to accurately simulate hurricane morphology (e.g. Zhu and Zhang, 2006), the results from this and the predecessor dry Jupiter-simulation studies are significant in part because they constitute 'no physics' matches to detailed GRS observations (in GCM modeling terminology, processes are separated into 'dynamics' and 'physics'; the latter includes phase changes, chemistry and subgrid-scale processes). What we are seeing on Jupiter are clouds lasting much longer than the time required to form them, which tends to disconnect the upper-tropospheric clouds from the vertical velocity, and this is different than what is often found on Earth below the tropopause.

Vertically, the outermost clouds on Jupiter span the 600–2000 hPa region, and are expected to be composed of ammonia at the top of this pressure range, and the chemical reactant ammonium hydrosulfide at the bottom. Ammonia has 40% less enthalpy of vaporization per mass than does water and resides at an altitude that is an order of magnitude less dense than Jupiter's water clouds, hence the ammonia clouds do not affect the thermodynamics like the water clouds, and for similar reasons the ammonium hydrosulfide clouds also play a minor role thermodynamically (cf. Palotai and Dowling, 2008, and references therein). As pointed out by Cho et al. (2001) and others, to the extent that potential vorticity is conserved following the motion, if Jupiter's outermost clouds are advected by the wind like passive tracers, then the

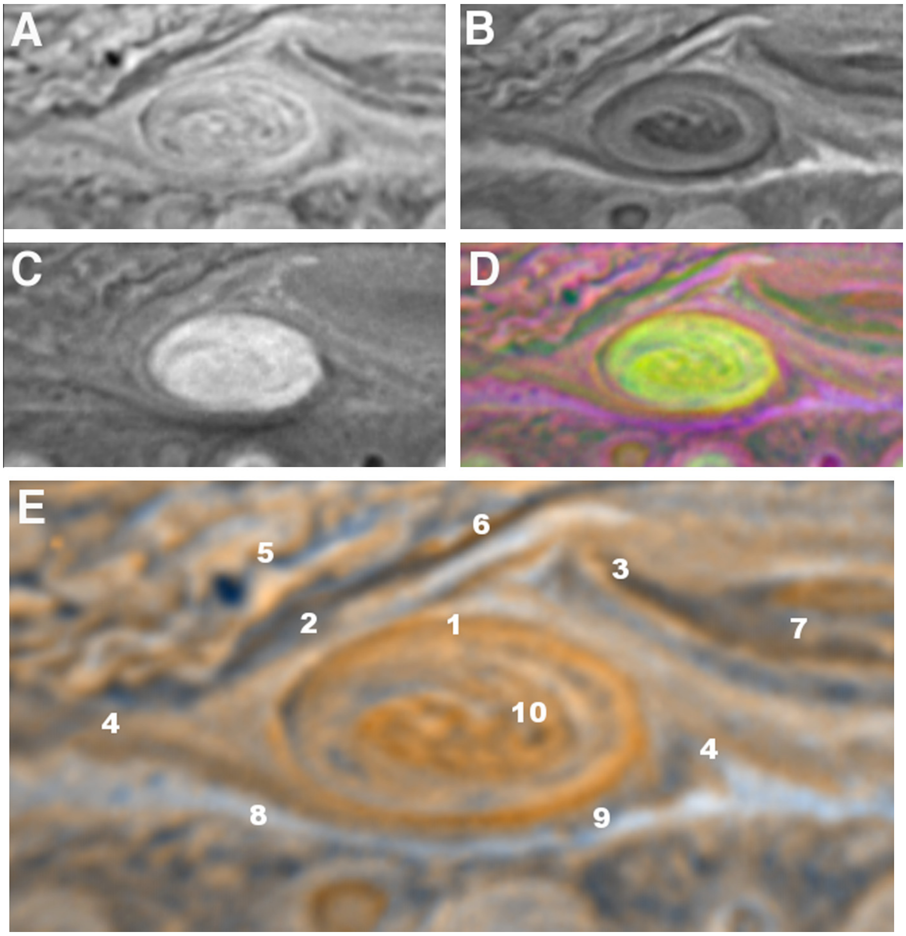

Fig. 1. Hubble Space Telescope (HST) images of Jupiter's Great Red Spot (GRS) taken on September 18, 1997. Each panel covers 40° in longitude and 20° in latitude, with North up and East to the right. (A) 953 nm, near-infrared image showing fine detail, (B) 410 nm, violet image showing strong absorption in the main oval, (C) 890 nm, methane-absorption band image revealing high-altitude clouds as bright, (D) false color composite constructed from panels A, B and C as red, blue and green channel images, and (E) false color composite created from panels A, B and their average as red, blue and green channels respectively. In panel E, the first four numbered features are from Cho et al. (2001), called the High Velocity Ring (feature 1), Lesser Northwest Hollow (feature 2), Greater Northeast Hollow (feature 3) and Cat's Eye Corners (feature 4). Both studies reproduce these four details, and in the present simulations we reproduce an additional six called the Greater Northwest Hollow (feature 5), Equatorial Hollow (feature 6), Northeast Recirculation (feature 7), Poleward Wind Side (feature 8), Poleward Lee Side (feature 9), and internal Dark Lane (feature 10).