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Saturn eddy momentum fluxes and convection: First estimates from Cassini images

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Abstract

We apply an automated cloud feature tracking algorithm to estimate eddy momentum fluxes in Saturn's southern hemisphere from Cassini Imaging Science Subsystem near-infrared continuum image sequences. Voyager Saturn manually tracked images had suggested no conversion of eddy to mean flow kinetic energy, but this was based on a small sample of <1000 wind vectors. The automated procedure we use for the Cassini data produces an order of magnitude more usable wind vectors with relatively unbiased sampling. Automated tracking is successful in and around the westward jet latitudes on Saturn but not in the vicinity of most eastward jets, where the linearity and non-discrete nature of cloud features produces ambiguous results. For the regions we are able to track, we find peak eddy fluxes $\sim 10\ m^2\,s^{-2}$ and a clear positive correlation between eddy momentum fluxes and meridional shear of the mean zonal wind, implying that eddies supply momentum to eastward jets and remove momentum from westward jets at a rate $\sim 5 \times 10^{-6}\ m\,s^{-2}$. The behavior we observe is similar to that seen on Jupiter, though with smaller eddy-mean kinetic energy conversion rates per unit mass of atmosphere ($3.3 \times 10^{-5}\ m^2\,s^{-3}$). We also use the appearance and rapid evolution of small bright features at continuum wavelengths, in combination with evidence from weak methane band images where possible, to diagnose the occurrence of moist convective storms on Saturn. Areal expansion rates imply updraft speeds of $\sim 1\ m\,s^{-1}$ over the convective anvil cloud area. As on Jupiter, convection preferentially occurs in cyclonic shear regions on Saturn, but unlike Jupiter, convection is also observed in eastward jet regions. With one possible exception, the large eddy fluxes seen in the cyclonic shear latitudes do not seem to be associated with convective events.

Keywords: Saturn, atmosphere; Atmospheres, dynamics; Meteorology; Jovian planets

1. Introduction

The defining dynamical property of the atmospheres of Jupiter and Saturn is their system of multiple alternating eastward and westward jets. On Jupiter, the horizontal shear regions between the jets are well-correlated with zonally oriented cloud albedo features ("belts" and "zones") that have been interpreted in terms of the sense of large-scale vertical motion (Hess and Panofsky, 1951; Ingersoll and Cuzzi, 1969); on Saturn a less consistent relationship between winds and clouds exists (Smith et al., 1981). Aside from Saturn's equatorial jet region, which may be variable in strength and/or cloud vertical structure (Sánchez-Lavega et al., 2004), and the 23° N jet on Jupiter (García-Melendo and Sánchez-Lavega, 2001), the other jets on both planets have been remarkably stable over several decades (Porco et al., 2003, 2005).

One of the major challenges to our understanding of these planets is to define the physical processes responsible for the maintenance of the jets and the banded cloud structure. Pro-

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posed mechanisms invoke either deep convective cylinders or shallow weather layer phenomena such as barotropic or baroclinic instability or moist convection as the ultimate source of energy for the jets (see Vasavada and Showman, 2005 for a review). Few observational constraints beyond the magnitude and spacing of the jets currently exist, though. In general, forcing for the mean zonal flow can consist of accelerations due to thermally direct mean meridional circulations associated with diabatic heating, or due to indirect circulations that respond to eddy momentum or heat flux convergences.

In recent years the Galileo and Cassini missions have provided some initial insights into these issues for Jupiter. For example, the assumed sense of the mean meridional overturning circulation, with rising motion in the bright zones and sinking motion in the darker belts, has been called into question by the finding that deep moist convective cloud features and lightning, and thus upwelling at the water condensation level, are restricted to the cyclonically sheared belt regions (Ingersoll et al., 2000; Porco et al., 2003). This would require an indirect circulation and thus a source of eddy forcing of the circulation. Early Voyager analyses of manually tracked cloud features implying horizontal eddy momentum flux convergence into the jets (Beebe et al., 1980; Ingersoll et al., 1981), which would be consistent with rising motion in the belts, were cast into doubt by Sromovsky et al. (1982). However, a more evenly sampled dataset of twice the size gave a similar result (Mitchell, 1982), and a recent automated tracking study of a much larger Cassini Jupiter flyby dataset, including analyses of various possible error sources, appears to support the original conclusion, albeit with a 2–4 times smaller inferred magnitude of the eddy-zonal kinetic energy conversion (Salyk et al., 2006).

On Saturn, however, the situation is less clear because the inherently lower image feature contrast limits the number of useful candidates for tracking. Ingersoll et al. (1984) and Sromovsky et al. (1986) attempted to derive eddy momentum fluxes from low-resolution Voyager flyby images, both finding negligible correlations between the eddy flux and the meridional shear of the zonal flow. Sromovsky et al. (1983) show mean meridional flow estimates for Saturn's northern hemisphere, including one westward jet with apparent mean flow divergence at cloud top but little systematic behavior elsewhere. Thus, few if any constraints on Saturn's large-scale dynamics at cloud level, other than the sense of the jets themselves, currently exist.

The Imaging Science Subsystem (ISS) experiment on the Cassini Orbiter mission (Porco et al., 2004) presents an opportunity to revisit these questions for Saturn with higher resolution, higher quality data over an extended period of time that will allow for climatologically representative estimates of eddy-mean flow interactions to be acquired. Initial assessments of the mean Saturn flow and its vertical structure (Porco et al., 2005) and distributions of vortices and spots (Vasavada et al., 2006) have been presented. In this paper we apply an automated cloud tracking technique to make an initial estimate of eddy momentum fluxes on Saturn. We also survey the distribution of convective features and assess the possibility of their role in the processes that maintain the jets on Saturn. The paper is organized as follows. Section 2 describes the dataset, processing, tracking algorithm, and convective feature identification approach. Eddy momentum flux distributions, their relationship to the mean flow, and tests of the sensitivity of the results to the tracking assumptions are described in Section 3. Convective feature identification, evolution, and relationship to the mean flow are explored in Section 4. We summarize our results and discuss their implications for ideas about the maintenance of the Saturn general circulation in Section 5.

2. Data and methods

2.1. Image selection and processing

We analyze 20 pairs of cylindrically projected ISS images separated by one planetary rotation obtained early in the Cassini orbital tour (5–8 February 2005), covering nearly 4 Saturn rotations at 19 km pixel^{-1} raw resolution. An imaging gap occurred in the middle of the period so that two independent sets of image pairs are available for each location observed. The images were acquired near apoapsis as part of a series of 3×3 mosaics covering most of Saturn's southern hemisphere, with a subspacecraft latitude of 5° S and a subsolar latitude of 19° S. Obstruction and shading of the northern hemisphere by Saturn's rings at this spacecraft and illumination geometry limit our analysis to the southern hemisphere. Individual frames near the limb and terminator were excluded from the analysis to minimize errors due to foreshortening and variations in seeing level. The images we analyze were acquired in a near-infrared continuum (CB2, 750 nm effective wavelength) filter that provides maximum feature contrast.

Images were flux calibrated using Cassini Imaging Science Subsystem CALibration (CISSCAL) software described in Porco et al. (2004). CISSCAL reads raw images, subtracts dark current and bias, divides by a flat field, corrects for nonlinearity and for the presence of a dust ring in the narrow angle camera field of view, and converts to I/F units. For filter combinations where absolute calibration has been possible, it applies another correction factor to bring results into line with that absolute calibration. A Minnaert function was applied to correct for large-scale illumination gradients before the images were cylindrically projected into 0.02 degree pixel^{-1} arrays, or $\sim$21 km pixel^{-1} at the equator. High-resolution narrow-angle images are navigated using IDL-based Modular Image and NAvigation Software (MINAS) developed at the Cassini Imaging Central Laboratory for Operations. MINAS reads various image formats, plots limb, ring, center, planet and ring grids, and star positions, accounts for ring obscuration, and fits limb and ring edges and star positions to correct camera pointing and enable mapping of globe surfaces. For our navigation of narrow-angle images, MINAS exploits near simultaneous wide-angle images that provide a visible planetary limb. Wide-angle images are scanned to locate the limb with sub-pixel precision. Approximate predicted pointing, extracted from binary C-kernels, is then matched to the scanned curve with a linear least-squares fit. Finally, a small boresight correction is applied to account for the known offset between the ISS Wide Angle and Narrow Angle Cameras. Navigated images are then