Icarus 219 (2012) 689–700

Contents lists available at SciVerse ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Constraints on Saturn's tropospheric general circulation from Cassini ISS images

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ARTICLE INFO

Article history:
Received 16 December 2011
Revised 19 March 2012
Accepted 30 March 2012
Available online 9 April 2012

Keywords:
Atmospheres, Dynamics
Meteorology
Saturn, Atmosphere

ABSTRACT

An automated cloud tracking algorithm is applied to Cassini Imaging Science Subsystem high-resolution apoapsis images of Saturn from 2005 and 2007 and moderate resolution images from 2011 and 2012 to define the near-global distribution of zonal winds and eddy momentum fluxes at the middle troposphere cloud level and in the upper troposphere haze. Improvements in the tracking algorithm combined with the greater feature contrast in the northern hemisphere during the approach to spring equinox allow for better rejection of erroneous wind vectors, a more objective assessment at any latitude of the quality of the mean zonal wind, and a population of winds comparable in size to that available for the much higher contrast atmosphere of Jupiter. Zonal winds at cloud level changed little between 2005 and 2007 at all latitudes sampled. Upper troposphere zonal winds derived from methane band images are $\sim$10 m s^{-1} weaker than cloud level winds in the cores of eastward jets and $\sim$5 m s^{-1} stronger on either side of the jet core, i.e., eastward jets appear to broaden with increasing altitude. In westward jet regions winds are approximately the same at both altitudes. Lateral eddy momentum fluxes are directed into eastward jet cores, including the strong equatorial jet, and away from westward jet cores and weaken with increasing altitude on the flanks of the eastward jets, consistent with the upward broadening of these jets. The conversion rate of eddy to mean zonal kinetic energy at the visible cloud level is larger in eastward jet regions (5.2×10^{-5} m^2 s^{-3}) and smaller in westward jet regions (1.6×10^{-5} m^2 s^{-3}) than the global mean value (4.1×10^{-5} m^2 s^{-3}). Overall the results are consistent with theories that suggest that the jets and the overturning meridional circulation at cloud level on Saturn are maintained at least in part by eddies due to instabilities of the large-scale flow near and/or below the cloud level.

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1. Introduction

One of the primary objectives of the Cassini Orbiter mission to Saturn has been to document Saturn's general circulation and to provide observational constraints on theories advanced to explain the circulation. Prior to Cassini, Saturn was less comprehensively observed than Jupiter, but 4 years of data from the Cassini nominal mission and new data from the extended mission now allow us to place Saturn on at least an equal footing with Jupiter despite the greater observational challenges presented by Saturn's multi-layer hazes and clouds.

The history of observations of Saturn's dynamics and the evolution of our understanding of the relevant processes up through the early years of the Cassini mission is discussed in the review by Del Genio et al. (2009). Like Jupiter, Saturn's major observed dynamical feature is its series of alternating eastward and westward jets, although whether Saturn actually has westward jets or merely eastward wind minima depends on the poorly known rotation rate of the deep atmosphere (Desch and Kaiser, 1981; Anderson and Schubert, 2007; Read et al., 2009a,b). The past few years has seen considerable progress in numerical modeling of jovian planet atmospheres targeted at understanding possible mechanisms for the observed jet structure. The modeling efforts fall into two broad categories – those that emphasize processes occurring in shallow weather layers near the visible cloud level (e.g., Lian and Showman, 2010; Liu and Schneider, 2010), and others that explore the ramifications of processes that extend through the deep molecular hydrogen envelopes of the jovian planet atmospheres (e.g., Heimpel and Aurnou, 2007; Kaspi et al., 2009). It has often been assumed that observations of the vertical structure of the wind itself differentiate these two classes of theories. However, it is possible for shallow forcing to influence the dynamics at depth and vice versa, so knowledge of the vertical structure of the mean zonal wind provides a valuable observational constraint but must be accompanied by other constraints to identify the relevant mechanisms (Showman et al., 2006; Del Genio et al., 2009).

The Cassini Imaging Science Subsystem (ISS; Porco et al., 2004) is one of the primary sources of information available to document dynamical processes operating in Saturn's atmosphere. The narrow-angle camera (NAC) allows individual regions on Saturn

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0019-1035/$ - see front matter Published by Elsevier Inc.
http://dx.doi.org/10.1016/j.icarus.2012.03.035

to be imaged at high resolution near distant apoapses, making hemispheric or near-global mosaics possible, while the accompanying wide-angle camera (WAC) provides simultaneous global views required for image navigation. ISS observes Saturn from the ultraviolet to the near-infrared, including both continuum and methane band filters, which produces information on clouds and hazes from Saturn's middle troposphere to stratosphere.

ISS images of the southern hemisphere of Saturn from the Cassini approach to Saturn and from early orbits at mostly moderate resolution have been used to document the latitudinal profile of mean zonal wind and its changes since the Voyager and Hubble eras (Porco et al., 2005; Vasavada et al., 2006; Sánchez-Lavega et al., 2007; García-Melendo et al., 2009); later images provide global coverage (García-Melendo et al., 2011). These studies primarily used either a manual tracking or a one-dimensional line shifting correlation approach. Manual tracking provides the highest confidence in individual wind vectors but its sampling is limited and the results can vary due to the subjective selection of targets. Line-shifting methods using a large segment of a latitude circle allow for very high latitudinal resolution but can only provide information on mean zonal winds, while potentially being influenced by large-scale waves whose phase speeds differ from the speed of the underlying wind (e.g., Del Genio and Rossow, 1990).

Del Genio et al. (2007) applied an automated cloud tracking approach to Saturn using a two-dimensional feature correlation method. The primary advantage of this method is that it uniformly samples an entire image in small areas corresponding to one or a few individual cloud features. It thus provides a more objective estimate of the actual mean wind (to the extent that the vectors that satisfy quality criteria are not a spatially biased sample). Furthermore it allows higher order statistics such as eddy momentum fluxes to be calculated since it yields two-dimensional information on the wind field at any level (three-dimensional if multiple filters are used). Because the features tracked are two-dimensional, though, it provides lower latitudinal resolution than one-dimensional techniques, and because it is automated it is subject to erroneous estimates of the wind in areas with little albedo contrast or mostly linear features.

Del Genio et al. (2007) applied the automated method to ISS Saturn near-infrared continuum filter images from early in the Cassini nominal mission. Because of the limitations mentioned above, we were only able to retrieve reliable wind estimates at some latitudes, the most problematic regions being the latitudes of the eastward jet cores. The early images also covered only the southern hemisphere due to obscuration of the northern hemisphere by the rings, ring shadows, and lack of insolation. Nonetheless the technique was good enough to provide an order of magnitude more sampling than was possible with the Voyager images (Ingersoll et al., 1984), while also allowing for the first credible estimates of the eddy momentum flux distribution on Saturn.

In this paper we extend our results to the 2007 time period, when Cassini was placed into a series of large daytime apoapsis orbits at low phase angle designed specifically to optimize large-scale imaging. These orbits give us our first views of the northern hemisphere of Saturn, permitting us to document the global wind characteristics but also giving us sufficient sampling to create regional composites of essential features of the dynamics. Additional recent images (2011–2012) allow us to track more of the previously obscured equatorial region as well. We also describe an improvement in our cloud tracking scheme that allows us to sample more of the eastward jet core regions with confidence, reduce uncertainties in our estimates of eddy momentum flux, and perform the first fully automated tracking of individual cloud feature areas in Saturn methane band images. Section 2 describes the data and methods used as well as several sensitivity tests of the algorithm. Section 3 documents the mean wind and eddy momentum flux distribution at a continuum wavelength, while Section 4 compares these to similar estimates at a methane band wavelength. Section 5 discusses the implications of our results for dynamical theories of jovian planet jet maintenance and the meridional overturning circulation.

2. Data and methods

2.1. Data selection and processing

The primary dataset used consists of ISS NAC continuum band (CB2; 750 nm) high-resolution ($\sim$17–23 km pixel^{-1}) images acquired on one early orbit in 2005 (Rev 3) and 3 of the later large dayside apoapsis orbits in 2007 (Revs 48, 49, 52). During Rev 48, limitations on data volume due to competition with other instruments for tape recorder space required 2×2 pixel summing, reducing the effective resolution. A total of 360 CB2 images taken from 28 mosaic pairs separated by approximately one Saturn rotation were analyzed. We also used methane band images taken with the ISS NAC MT2 filter (727 nm) simultaneously with the CB2 images on Revs 3 and 52. The MT2 images on the latter orbit were 2×2 summed. A total of 180 MT2 images from 16 mosaic pairs were analyzed. There are no data between 6°S and 18°N during these time periods due either to ring shadow or obscuration or image sampling. However, 20 lower resolution (103–172 km pixel^{-1}) WAC CB2s acquired during the extended mission in 2011–2012 (Revs 145 and 159–161), by which time low northern latitudes were illuminated, have allowed us to extend northern hemisphere coverage down to 5.5°N. The details of each imaging period are given in Table 1. The subsolar latitude for the NAC images ranged from 22.6°S during Rev 3, to 9.9°S during Rev 52. For the recent WACs the subsolar latitude ranged from 8.4°N during Rev 145 to 13.2°N during Rev 161.

Image calibration, photometric correction, and navigation procedures are described fully in Del Genio et al. (2007). Briefly, we use Cassini Imaging Science Subsystem CALibration (CISSCAL) software (Porco et al., 2004; see also R. West, 2005, unpublished manuscript, available from the Planetary Data System) to subtract dark current and bias, divide by a flat field, correct for nonlinearity and dust rings, adjust to absolute calibrations when available, and convert to I/F units using the insolation at Saturn's distance as a reference. A Minnaert function is then applied to partly correct for large-scale illumination gradients. Navigation of NACs exploits near-simultaneous WACs to locate the limb with sub-pixel precision, match approximate predicted pointing from binary C-kernels to the limb curve with a least-squares fit, and then apply a small WAC–NAC boresight correction. Navigated images are finally mapped into a cylindrical (rectangular) projection in the planetocentric latitude system.

Near-infrared images of Saturn are affected both by the optically thick ($\tau \sim 10$) upper troposphere haze that is estimated to extend from $\sim$100 to 400 mbar and by the ammonia cloud deck that begins in the vicinity of $\sim$1 bar (Karkoschka and Tomasko, 2005; Pérez-Hoyos et al., 2005). Thus temporal and spatial variations in the thickness of the tropospheric haze affect the level to which CB2 sees. Fig. 1 (left) shows a typical 2007 WAC CB2 image of Saturn. The two hemispheres have very different appearances, the northern hemisphere being darker but having much greater small-scale feature contrast than the southern hemisphere. Fletcher et al. (2011) find a factor of 1.5–2.0 seasonal difference in the 5 μm opacity of the tropospheric haze, with opacity being lower in the winter (northern) hemisphere. The thinner northern haze apparently allows CB2 images to see deeper into Saturn's atmosphere there. Fig. 2 (solid curves) shows that mean I/F for the features we tracked in 2007 was lower in the northern hemisphere