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Seasonal evolution of Saturn's polar temperatures and composition

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ABSTRACT

The seasonal evolution of Saturn's polar atmospheric temperatures and hydrocarbon composition is derived from a decade of Cassini Composite Infrared Spectrometer (CIRS) 7–16 μm thermal infrared spectroscopy. We construct a near-continuous record of atmospheric variability poleward of 60° from northern winter/southern summer (2004, $L_s = 293°$) through the equinox (2009, $L_s = 0°$) to northern spring/southern autumn (2014, $L_s = 56°$). The hot tropospheric polar cyclones that are entrained by prograde jets within 2–3° of each pole, and the hexagonal shape of the north polar belt, are both persistent features throughout the decade of observations. The hexagon vertices rotated westward by ≈30° longitude between March 2007 and April 2013, confirming that they are not stationary in the Voyager-defined System III longitude system as previously thought. Tropospheric temperature contrasts between the cool polar zones (near 80–85°) and warm polar belts (near 75–80°) have varied in both hemispheres, resulting in changes to the vertical windshear on the zonal jets in the upper troposphere and lower stratosphere. The extended region of south polar stratospheric emission has cooled dramatically poleward of the sharp temperature gradient near 75°S (by approximately −5 K/yr), coinciding with a depletion in the abundances of acetylene (0.030 ± 0.005 ppm/yr) and ethane (0.35 ± 0.1 ppm/yr), and suggestive of stratospheric upwelling with vertical wind speeds of $w \approx +0.1$ mm/s. The upwelling appears most intense within 5° latitude of the south pole. This is mirrored by a general warming of the northern polar stratosphere (+5 K/yr) and an enhancement in acetylene (0.030 ± 0.003 ppm/yr) and ethane (0.45 ± 0.1 ppm/yr) abundances that appears to be most intense poleward of 75°N, suggesting subsidence at $w \approx -0.15$ mm/s. However, the sharp gradient in stratospheric emission expected to form near 75°N by northern summer solstice (2017, $L_s = 90°$) has not yet been observed, so we continue to await the development of a northern summer stratospheric vortex. The peak stratospheric warming in the north occurs at lower pressure levels ($p < 1$ mbar) than the peak stratospheric cooling in the south ($p > 1$ mbar). Vertical motions are derived from both the temperature field (using the measured rates of temperature change and the deviations from the expectations of radiative equilibrium models) and hydrocarbon distributions (solving the continuity equation). Vertical velocities tend towards zero in the upper troposphere where seasonal temperature contrasts are smaller, except within the tropospheric polar cyclones where $w \approx \pm 0.02$ mm/s. North polar minima in tropospheric and stratospheric temperatures were detected in 2008–2010 (lagging one season, or 6–8 years, behind winter solstice); south polar maxima appear to have occurred before the start of the Cassini observations (1–2 years after summer solstice), consistent with the expectations of radiative climate models. The influence of dynamics implies that the coldest winter temperatures occur in the 75–80° region in the stratosphere, and in the cool polar zones in the troposphere, rather than at the poles themselves. In addition to vertical motions, we propose that the UV-absorbent polar stratospheric aerosols entrained within Saturn's vortices contribute significantly to the radiative budget at the poles, adding to the localised enhancement in the south polar cooling and north polar warming poleward of ±75°.

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1. Introduction

The polar regions of the giant planets exhibit some of the most complex environmental conditions found in the outer Solar System. They are the apex of a planet-wide circulation system, where the organised pattern of zonal banding gives way to the more mottled appearance of the high latitudes. Furthermore, they are the site of the closest connection between the neutral atmosphere and the charged magnetosphere via auroral activity, and the unusual chemistry and aerosol production generated by this energy injection. Given Saturn's 26.7° obliquity, its poles are subjected to extremes of insolation over its 29.5-year orbit, spending a decade in polar night before emerging into spring sunlight. As the polar winter is hidden from Earth-based observers, only an orbiting spacecraft can provide the vantage point and longevity to study the evolving polar atmosphere as the seasons change. After a decade of exploration (2004–2014, planetocentric solar longitudes of L_s = 293–56°), Cassini has provided the most comprehensive view of a seasonally-evolving giant planet ever obtained. This study focuses on temporal evolution at Saturn's poles as southern summer became southern autumn, and northern winter became northern spring.

This investigation builds upon the snapshot of polar conditions observed in 2005–2007 (Fletcher et al., 2008) in the thermal infrared (7–1000 μm) by the Cassini Composite Infrared Spectrometer (CIRS, Flasar et al., 2004). Those observations revealed a striking asymmetry in temperature from the summer to the winter pole, with an extended warm stratospheric 'hood' over the summer pole suggesting the presence of a summer stratospheric vortex (approximately 75–90°S planetographic latitude), possibly entraining unique polar aerosols, that was absent from the cold winter pole. In addition, compact and warm cyclonic vortices were discovered within 2–3° of both poles (Orton and Yanamandra-Fisher, 2005; Fletcher et al., 2008), suggesting that these cyclonic polar vortices (and their 'hurricane-like' eyewalls, Sánchez-Lavega et al., 2006; Dyudina et al., 2008, 2009; Baines et al., 2009) are persistent features on Saturn, irrespective of the season. We refer to these as the 'north polar cyclone' (NPC) and 'south polar cyclone' (SPC), respectively. We use a decade of Cassini observations to study the stability of the polar cyclones, the seasonal evolution of the summer stratospheric vortices, and to search for evidence of compositional trends in the polar regions.

Previous studies of Saturn's evolving atmospheric structure (Fletcher et al., 2010; Li et al., 2010, 2013; Guerlet et al., 2011; Sinclair et al., 2013, 2014) have used nadir and limb observations acquired while Cassini was in a near-equatorial orbit, making observations of the highest latitudes difficult. Fletcher et al. (2010) discovered a cooling of the summer stratosphere over a five-year period in pre-equinox (August 2009) CIRS spectra, consistent with the expectations of radiative cooling (Greathouse et al., 2008), which suggested a weakening of the peripheral stratospheric jet entraining the vortex. This southern cooling was observed through to 2010 by Sinclair et al. (2013). A minimum in the northern stratospheric temperatures was observed at 78–82°N, the latitude of the hexagonal wave in Saturn's troposphere (Godfrey, 1988). Poleward of the hexagon, the north pole was warmer than expected due to subsidence and adiabatic heating, despite the winter conditions.

The timescale for the formation of the summer stratospheric vortex was not constrained by observations prior to Cassini's arrival. Mid-infrared imaging from Keck in February 2004 ($L_s = 287.4°$) showed that the elevated south polar emission was already present (Orton and Yanamandra-Fisher, 2005), and must have developed prior to southern summer solstice (October 2002, $L_s = 270°$, G. Orton, personal communication). Intriguingly, stratosphere-sensitive imaging from NASA's Infrared Telescope Facility in March 1989 ($L_s = 104.5°$, after northern summer solstice) (Gezari et al., 1989) showed enhanced emission from the north polar region, suggesting that the Cassini mission should expect the onset of a warm northern summer stratospheric vortex between now and the northern summer solstice in May 2017 ($L_s = 90°$). This study aims to constrain the timescale for the seasonal onset of the northern stratospheric vortex and the dissipation of the southern stratospheric vortex.

In addition to these thermal changes, Sinclair et al. (2013) used two epochs of low-spectral resolution CIRS data ($\Delta\nu = 15$ cm^{-1} apodised) acquired from low-inclination orbits to demonstrate that both ethane (C_2H_6) and acetylene (C_2H_2) were enhanced at the south pole but had decreased in concentration between 2005 and 2010. In this work we significantly extend the temporal and spatial coverage of the CIRS dataset and the robustness of the spectral inversions by considering all available data at $\Delta\nu = 2.5$ cm^{-1} and $\Delta\nu = 15.0$ cm^{-1} spectral resolution, particularly those acquired during Cassini's inclined orbits, as described in Section 2. The methods used to invert these spectra are described in Section 3, and the resulting temperature and composition variability is presented in Section 4. The results are compared with the expectations of seasonal climate models (e.g., Greathouse et al., 2008; Friedson and Moses, 2012; Guerlet et al., 2014), with implications for horizontal and vertical motions in Saturn's middle atmosphere discussed in Section 5.

2. Polar observations

2.1. Cassini/CIRS data

Coverage of Saturn's high latitudes has been provided by Cassini in clusters of observations whenever the orbital inclination rose out of Saturn's equatorial plane. Our first study of Saturn's polar region (Fletcher et al., 2008) used data acquired during a '180° transfer' manoeuvre between July 2006 and June 2007, when the orbital inclination was increased via multiple Titan flybys. Since then, Cassini has returned to these inclined orbits on two further occasions. Cassini ended its prime mission (2008) and started its equinox mission in an inclined phase (from September 2007 to April 2009), and is currently in the first inclined phase of the solstice mission (May 2012 to March 2015). Cassini exceeded an inclination of 40° from October 2012 to October 2014, and reached a peak inclination of 61.7° in April–May 2013. A second and final inclined phase is planned for January to November 2016, before the start of Cassini's proximal orbits (close-in, high-inclination phase) at the end of the solstice mission.

Saturn's polar temperatures and gaseous composition can be determined by inversion of mid-infrared spectra from CIRS. This study utilises only one of the two interferometers that comprise the CIRS instrument, focusing on the 7–16 μm (600–1400 cm^{-1}) spectra measured by the Michelson interferometer, which has a higher spatial resolution than observations taken using the longer wavelength ($\lambda > 16$ μm) polarising interferometer. Spectra are recorded with two 1×10 HgCdTe focal plane arrays (FP3, 600–1100 cm^{-1}; and FP4, 1100–1500 cm^{-1}) with an instantaneous field of view of 0.27×0.27 mrad yielding spatial resolutions of 0.5–3.0° latitude depending on the type of observation. Typically, the CIRS team designs a range of observations that are given priority on the spacecraft for a set duration (multiple hours, usually covering one or two Saturn rotations). One of the key advantages of CIRS is its tuneable spectral resolution from 0.5 to 15.0 cm^{-1} (apodised): it is usual for the lowest spectral resolution to be used in scanning the focal planes from north to south along Saturn's central meridian as it rotates, whereas the higher spectral resolutions are used in a