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Seasonal variations in Titan's middle atmosphere during the northern spring derived from Cassini/CIRS observations

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ABSTRACT

We analyzed spectra acquired at the limb of Titan in the 2006–2013 period by the Cassini/Composite Infrared Spectrometer (CIRS) in order to monitor the seasonal evolution of the thermal, gas composition and aerosol spatial distributions. We are primarily interested here in the seasonal changes after the northern spring equinox and interpret our results in term of global circulation seasonal changes. Data cover the 600–1500 cm^{-1} spectral range at a resolution of 0.5 or 15.5 cm^{-1} and probe the 150–500 km vertical range with a vertical resolution of about 30 km. Retrievals of the limb spectra acquired at 15.5 cm^{-1} resolution allowed us to derive eight global maps of temperature, aerosols and C_2H_2, C_2H_6 and HCN molecular mixing ratios between July 2009 and May 2013. In order to have a better understanding of the global changes taking place after the northern spring equinox, we analyzed 0.5 cm^{-1} resolution limb spectra to infer the mixing ratio profiles of 10 molecules for some latitudes. These profiles are compared with CIRS observations performed during the northern winter. Our observations are compatible with the coexistence of two circulation cells upwelling at mid-latitudes and downwelling at both poles from at last January 2010 to at least June 2010. One year later, in June 2011, there are indications that the global circulation had reversed compared to the winter situation, with a single pole-to-pole cell upwelling at the north pole and downwelling at the south pole. Our observations show that in December 2011, this new pole-to-pole cell has settled with a downward velocity of 4.4 mm/s at 450 km above the south pole. Therefore, in about two years after the equinox, the global circulation observed during the northern winter has totally reversed, which is in agreement with the predictions of general circulation models. We observe a sudden unexpected temperature decrease above the south pole in February 2012, which is probably related to the strong enhancement of molecular gas in this region, acting as radiative coolers. In July and November 2012, we observe a detached haze layer located around 320–330 km, which is comparable to the altitude of the detached haze layer observed by the Cassini Imaging Science Subsystem (ISS) in the UV.

1. Introduction

Titan's atmosphere has one of the most complex chemistry in the Solar System, which is based on the photodissociation of N_2 (98% in the middle atmosphere) and CH_4 (between 1% and 1.5% in the middle atmosphere Niemann et al. (2010), Lellouch et al. (2014), Maltagliati et al. (2015), Bézard (2014)). In the upper atmosphere, typically above 800 km, the combined photochemistry of N_2 and CH_4, through 80–200 nm solar radiation, energetic photoelectrons (produced by solar X-ray and EUV radiations) and Saturnian magnetospheric electrons, leads to the formation of the ionosphere, where very complex positive and negative ions (Waite et al., 2005; Coates et al., 2007) subsequently recombine to form complex macromolecules that agglomerate into monomers and then in fractals aerosols while descending through the atmo-

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sphere (Lavvas et al., 2011). Dissociation of N_2, leads to the formation of nitriles, HCN being by far the most abundant. Around 800 km, CH_4 photodissociation by the intense solar Lyman α line mostly drives the hydrocarbons photochemistry, while in the 200–300 km region, CH_4 dissociation is driven by catalytic reactions via dissociation of C_2H_2 and other molecules whose radicals attack CH_4. In the present study, we are interested in the region between 150 and 500 km.

Dynamics, which is driven by the atmospheric thermal latitudinal gradients, redistributes molecules and aerosols, and also impacts the temperature field through vertical air motions and horizontal heat transport. Aerosols and molecules also affect the temperature by absorbing the solar radiation and emitting in the thermal infrared range. Therefore, complex couplings between photochemistry and dynamics exist in Titan's atmosphere. Associated with the meridional circulation and latitudinal thermal structure are strong zonal jets, particularly in the winter hemisphere (Flasar et al., 2005; Achterberg et al., 2008), which act as "a containment vessel" for the so-called polar vortex. Polar vortex confines molecular species, and because of the air subsidence occurring at the winter pole, these species are strongly enriched in the mesosphere/stratosphere inside the vortex. This was observed with CIRS during the winter above the north pole (Coustenis et al., 2007; Teanby et al., 2006, 2007, 2008, 2009a; Vinatier et al., 2007, 2010b).

Moreover, because of the 26.73° obliquity of Titan, its atmosphere experiences strong seasonal variations of insolation. Titan's obliquity is comparable to the Earth's 23.5° and in analogy to the dynamics of the Earth middle atmosphere, the 2D thermal and compositional structure has been interpreted in terms of pole-to-pole cell redistributing heat meridionally from the sunlit pole to the winter pole via adiabatic cooling and heating under solstitial conditions. During equinoxial conditions, a two cell pattern is predicted with upward motion and adiabatic cooling at mid-latitudes and downward motion with adiabatic heating at both poles. The transition from equinoxial to solstitial conditions is fairly rapid in the Earth middle atmosphere as the radiative time constant at the stratopause is only 5 days (or ~0.015 Earth year). In Titan's stratosphere, the radiative constant is ~0.02 Titan year over the altitude range 200–450 km (Strobel et al., 2010) and thus scales with Earth's time constant and validates the analogy. In agreement with this analogy, General Circulation Models (GCMs) of Titan's atmosphere (Hourdin et al., 2004; Lebonnois et al., 2012; Newman et al., 2011) predict that the total reversal of the pole-to-pole circulation occurs within about one or two years after the equinox.

The northern spring equinox occurred on 2009 August 11 (L_s = 0°). In June 2011, Teanby et al. (2012) observed for the first time above the south pole an enrichment at high altitude of HC_3N, HCN and C_2H_2, which was the first evidence of the global post equinox dynamical changes with the beginning of an air subsidence above the south pole. Additionally, Jennings et al. (2012) detected with CIRS the emission feature at 220 cm^{-1} (attributed to a cloud of condensed material) at the south pole in July 2012, while it was only seen previously inside the northern polar vortex. In May 2012, a very interesting cloud, with an unexpected vertical extent in the stratosphere, was observed for the first time by the Cassini/Imaging Science Subsystem (ISS) above the south pole (West et al., 2013). This cloud is at least partly composed of HCN ice (de Kok et al., 2014).

Cassini also brought some information regarding the seasonal evolution of the aerosol spatial distribution around the equinox. During the northern winter, the meridional distribution of Titan's aerosols was also constrained from near infrared observations of the Cassini Visual and Infrared Mapping Spectrometer (VIMS) by Rannou et al. (2010) and from CIRS mid infrared observations (Vinatier et al., 2010a). From observations of ISS, West et al. (2011) inferred the seasonal evolution of the altitude of the detached haze layer which was localized around 500 km during the winter in 2007 and dropped to 380 km in 2010.

One important question which this paper addresses is when does the transition from the single pole-to-pole circulation and breakdown of the winter polar vortex occur in Titan's stratosphere. We answer this question by deriving, from the analysis of CIRS limb spectra, the seasonal variations of temperature, molecular and aerosol mixing ratio spatial distributions between October 2006 (northern winter) and May 2013 (northern spring). Sections 2 and 3 describe the observations used for this study and the retrieval method, respectively. Results and their implications regarding the global dynamic changes are detailed in Section 4 and discussed in Section 5.

2. Observations

We analyze here the thermal emission of Titan's limb acquired by CIRS. CIRS is a Fourier Transform spectrometer that record spectra in the 20–1500 cm^{-1} spectral range, through three focal planes (FP1, FP3 and FP4). We focus here on the study of spectra acquired by the FP3 (570–1125 cm^{-1}) and the FP4 (1050–1495 cm^{-1}) focal planes, each composed of 10 adjacent detectors. During a limb observation, each detector array is positioned so that each detector probes a different altitude above a given latitude/longitude. At a given time on a limb observation, five detectors of FP3 and five detectors of FP4 acquire spectra simultaneously, the subsequent spectra are then acquired by the five other detectors of each focal planes. During about one to two hours, the 10 detectors arrays are positioned so that each detector record data from the same altitude. Then, FP3 and FP4 arrays are positioned so that they observe higher altitudes in the atmosphere. The field-of-view of each detector is 0.273 mrad. Limb observations used in this study, were acquired typically at distances between 100,000 and 180,000 km of Titan's surface, which results in a vertical resolution varying between 27 and 49 km, which is comparable to the pressure scale height in Titan's stratosphere (~40 km). During a single limb observation, lines-of-sight span altitudes between the surface and 600–700 km (depending of the spatial resolution of the observations). More details regarding CIRS and its different observing modes are given by Kunde et al. (1996), Flasar et al. (2004).

We utilized here two types of datasets: (i) spectra acquired at a spectral resolution of 0.5 cm^{-1} above a given latitude/longitude during a given flyby; (ii) spectra acquired at a spectral resolution of 15.5 cm^{-1}, above several latitudes/longitudes during a given flyby. Both types of datasets are acquired during about 4 h. It takes about 52 s to acquire a spectrum at a resolution of 0.5 cm^{-1}, while a spectrum at a resolution of 15.5 cm^{-1} needs ten times less acquisition duration. As a result, during about 4 h, a typical number of 20 latitudes are observed at a resolution of 15.5 cm^{-1}, while only one latitude is probed with a spectral resolution of 0.5 cm^{-1}.

Both datasets have their own advantages. With observations at 0.5 cm^{-1} resolution, we are able to infer the mixing ratio profiles of about 10 molecules at a given surface coordinate and a given time, while spectra at 15.5 cm^{-1} resolution allows us to infer vertical mixing ratio profiles of about 3 molecules over an entire hemisphere with a typical spatial resolution of 5° latitude at a given date.

In order to improve the signal-to-noise, we performed averages of limb spectra per detector, which corresponds to adjacent altitude bins of about 30–45 km (typically equal to the vertical resolution of the limb observations). Thus, about 10–15 averaged limb spectra were used to retrieved each vertical profiles of physical parameters.

Some of the observed limb spectra have a continuum with negative radiance in some spectral regions, mostly around 1000 cm^{-1}, and other displayed continuum values that seemed to be shifted in