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Microphysical modeling of Titan's detached haze layer in a 3D GCM

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ABSTRACT

We use a 3D GCM with coupled aerosol microphysics to investigate the formation and seasonal cycle of the detached haze layer in Titan's upper atmosphere. The base of the detached haze layer is defined by a local minimum in the vertical extinction profile. The detached haze is seen at all latitudes including the south pole as seen in Cassini images from 2005–2012. The layer merges into the winter polar haze at high latitudes where the Hadley circulation carries the particles downward. The hemisphere in which the haze merges with the polar haze varies with season. We find that the base of the detached haze layer occurs where there is a near balance between vertical winds and particle fall velocities. Generally the vertical variation of particle concentration in the detached haze region is simply controlled by sedimentation, so the concentration and the extinction vary roughly in proportion to air density. This variation explains why the upper part of the main haze layer, and the bulk of the detached haze layer follow exponential profiles. However, the shape of the profile is modified in regions where the vertical wind velocity is comparable to the particle fall velocity. Our simulations closely match the period when the base of the detached layer in the tropics is observed to begin its seasonal drop in altitude, and the total range of the altitude drop. However, the simulations have the base of the detached layer about 100 km lower than observed, and the time for the base to descend is slower in the simulations than observed. These differences may point to the model having somewhat lower vertical winds than occur on Titan, or somewhat too large of particle sizes, or some combination of both. Our model is consistent with a dynamical origin for the detached haze rather than a chemical or microphysical one. This balance between the vertical wind and particle fall velocities occurs throughout the summer hemisphere and tropics. The particle concentration gradients that are established in the summer hemisphere are transported to the winter hemisphere by meridional winds from the overturning Hadley cell. Our model is consistent with the disappearance of the detached haze layer in early 2014. Our simulations predict the detached haze and gap will reemerge at its original high altitude between mid 2014 and early 2015.

1. Introduction

Titan's detached haze layer was first observed by Voyager as a region of enhanced scattering at an altitude of about 350 km overlying a region with a relative minimum of scattering near 320 km at all latitudes south of 45°N (Rages and Pollack, 1983). We refer to the region of relative minimum in extinction as a gap separating the detached haze layer from the main haze layer on Titan. As discussed below the detached haze layer is something of an illusion. There is no well-defined top to the haze layer. Instead the extinction declines quasi-exponentially with altitude until the signal is lost in the noise of the observations. Likely the haze extends up to 1000 km above the surface where Cassini has directly observed high molecular weight compounds during its close flybys (Waite et al., 2007). The haze mostly distributes itself in inverse proportion to the particle fall velocity. However, waves observed in the haze suggest more complicated transport mechanisms contribute to the haze distribution as well (Koskinen et al., 2011). The gap is a minimum in extinction, observed above the noise level, where interesting physics may occur. Details of the haze particles were first observed by Rages and Pollack (1983), who retrieved an aerosol number density of 0.2 particles cm^{-3} and a particle radius of 0.3–0.4 μm in the detached haze layer between 300 and 350 km.

Cassini provided an abundance of observations of Titan's detached haze and its associated gap, the altitude of which was observed to change over time (West et al., 2011). The gap and associated detached layer drop about 200 km in altitude during the Titan spring season between Ls 300 and Ls 30. Ls stands for

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solar longitude and breaks the Titan year up into 360 degrees. Ls 0 indicates the northern spring equinox, which Titan went through in August of 2009. The Huygens probe landed on Titan in January of 2005.

The detached haze layer on Titan extends over most latitudes and connects to the top of the winter polar hood at 55°N latitude as seen in Fig. 1. The polar hood on Titan is a region of enhanced extinction associated with the downwelling branch of the pole-to-pole Hadley cell. Rages and Pollack (1983) observed a polar hood in the northern hemisphere, but not in the southern hemisphere, just after spring equinox. When Cassini arrived at Titan in the northern winter, it also observed a northern polar hood. West et al. (2013 DPS) reported that 1000 terrestrial days, or 1/10 of a Titan year, after the northern spring equinox, a polar hood existed in both hemispheres.

The decrease in altitude of the detached haze layer and the appearance of the southern polar hood following the northern spring equinox are effects of the more general seasonal cycle of the dynamics in which a pole-to-pole Hadley cell reverses direction with the seasons. Evidence of the reversal of the Hadley cell after the equinox can be seen in the abundance of trace gas species (Teanby et al., 2012).

There are two types of explanations for the origin of Titan's detached haze: microphysical and dynamical. The dynamical explanation, originally suggested using a 1-D model by Toon et al. (1992), is that the gap separating the detached haze layer from the lower main haze layer is caused by rising motions which are fast enough to suspend the haze particles. In two dimensions, upwelling in Titans summer hemisphere lifts haze particles with fall velocities smaller than the wind speed, but particles with high fall velocities are depleted in the low extinction region under the detached haze. Then aerosols are transported horizontally to the winter pole where they descend. Rannou et al. (2002, 2004) demonstrated this idea works using a 2D GCM with coupled aerosol microphysics. Their model created a detached haze layer with extinctions close to observations. They were also able to model the seasonal cycle of the detached layer and its altitude. Although their detached haze is about 70 km below that of more recent observations leading up to the equinox, their model shows a strong drop in altitude of the haze layer around northern spring equinox, similar to that found in observations by West et al. (2011). However, their model did not show a bimodal particle distribution consistent with theory and observations. Cours et al. (2011) also argue for a dynamical origin of Titan's detached haze layer based on evidence from a bimodal particle population in the detached haze. They find that the two populations of particles making up the detached haze include small particles being formed in the upper atmosphere and falling into the detached layer and larger particles dynamically transported up from the main haze layer below. They conclude from analysis of scattered light in Cassini ISS and UVIS observations that the particles in the detached haze have an effective radius of 0.15 μm around 500 km. Further evidence cited by Cours et al. (2011) for a dynamical origin of the detached haze is that the long timescale needed to create large aggregate particles exceeds their sedimentation timescale. The submicrometric particles found in the detached haze by Rages and Pollack (1983) and Cours et al. (2011) cannot be obtained with a microphysical model alone. We hypothesize that a critical test for Cours et al.'s dynamical theory is having mixed particle sizes including large submicron particles and the near balance between vertical wind speeds and the particle fall velocities in the region of the detached haze layer, and their change with seasons as this layer changes altitude. Other expectations of the dynamical theory, which were noted by West et al. (2011), include the particles following streamlines that tend toward vertical near the summer pole, assuming the particles follow mean streamlines. However, other processes such as waves may affect the transport of aerosols as well.

Lavvas et al. (2009) suggested an alternative explanation for the detached haze layer based on microphysics. They used a one-dimensional microphysical model to show that coagulation of spherical monomer particles into fractal aggregates can lead to a deficit in extinction, since larger fractal particles, created by coagulation as particles descend, tend to have less extinction per unit mass. This model reproduces a deficit in the vertical extinction profile that is very similar to observations by Liang et al. (2007). Their best fit model parameters include a particle size of 40 nm and a number density of 30 particles cm^{-3} in Titan's detached haze layer. Lavvas et al. (2009) did not offer an explanation for the vertical movement of the haze. We hypothesize that the critical test for the Lavvas microphysical theory is the sudden shift from monomers to fractal particles in the region of the gap, or in other words, a change in particle shape and size across the gap.

In this paper we use a 3-dimensional GCM with coupled microphysics to extend the efforts of the previous studies explaining the origin and seasonal evolution of Titan's detached haze layer. We can test the hypotheses for the formation of the detached haze, mentioned above, with our model by investigating the microphysical and dynamical conditions under which our model produces a

Fig. 1. Image of Titan taken by the Cassini Imaging Science Subsystem at 445 nm on April 19th, 2011. On the left is the whole disk of Titan. A white box at the equatorial limb has been enlarged on the right to show the main and detached haze.