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Simulating Titan's aerosols in a three dimensional general circulation model

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ABSTRACT

We present results from a new three dimensional GCM with a complete microphysics treatment of the aerosols. We used the Titan Community Atmospheres Model (CAM), to which we have coupled the Community Aerosol and Radiation Model for Atmospheres (CARMA). This model was unable to reproduce superrotating winds without an ad hoc forcing of the zonal winds. Our model was validated by comparing the extinction, optical depth, phase functions, and number densities with data from Cassini and Huygens, as well as other space based and ground based observations. These comparisons allowed us to constrain the microphysical properties of Titan's haze in the tropics at the time of the Huygens descent. Our best fit of the free aerosol parameters include a haze production rate of 1×10^{-14} g cm^{-2} s^{-1} and a charge to radius ratio on the particles of 7.5 e^{-}/μm. Despite recent evidence of equatorial precipitation on Titan, we find the aerosols are only slowly removed by rainfall, less than once in 50 Earth years. One way to fit the wavelength dependence of the optical depth is to model the haze as fractal particles with a changing fractal dimension of 2 above 80 km that increases to 2.8 below 30 km. We investigate the spatial and seasonal variability of Titan's haze in our model. We find that the haze particle size and number density responds to the dynamics and creates a seasonal cycle in Titan's albedo.

1. Introduction

Titan is the only Moon in our Solar System with an appreciable atmosphere. Its atmosphere contains an optically thick, sunlight absorbing haze composed of organic compounds. Numerous models of this haze have been constructed and compared with data from the Voyager and Cassini spacecraft. To date complete microphysical models have been implemented in one (Toon et al., 1980; Toon et al., 1992; Lavvas et al., 2010), two (Rannou et al., 2004), or more recently three dimensions (Lebonnois et al., 2012a). Here we report simulations and comparisons with observations using a three-dimensional model with complete microphysics.

Understanding the aerosols on Titan is imperative for understanding the atmosphere as a whole. Organic aerosols are produced in Titan's upper atmosphere through complex photochemistry involving the destruction of methane (Yung et al., 1984; Wilson and Atreya, 2004). The methane (2%) and nitrogen (98%) in Titan's upper atmosphere dissociate because of UV photons or high energy particles to create a variety of organic compounds including: ethane (C_2H_6), ethene (C_2H_4), acetylene (C_2H_2), hydrogen cyanide (HCN) and a host of other more complex organics. Chemical and aerosol modeling suggests that small, 0.05 μm, spherical monomers are produced from the photochemistry and ensuing coagulation hundreds of kilometers above Titan's surface (Wilson and Atreya, 2004; Tomasko et al., 2008b; Lavvas et al., 2010). The aerosol monomers are probably insoluble in hydrocarbons and have low volatility, so they do not evaporate (McKay et al., 2001; Coll et al., 1999). As the monomers drift downward they coagulate further into fractal aggregates reaching sizes near a half micron in the stratosphere (Cabane et al., 1993; Lavvas et al., 2010). As the particles coagulate and fall they likely act as seed nuclei for the condensation of methane, ethane and other condensable hydrocarbons. However, models suggest that only about 1% of the aerosols are removed from the atmosphere through precipitation (Barth and Toon, 2006). The vast majority of the aerosols may be deposited on the surface through dry deposition.

1.1. Constraining aerosol properties

There is a long history of observations on Titan that can be used to validate and constrain aerosol models. Rages and Pollack (1983) used Voyager data to measure the extinction profile in the upper atmosphere of Titan. They discovered the detached haze layer

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above 350 km. West et al. (2011) found that the height of the detached haze layer falls from over 500 km to 350 km around equinox. Ground based studies of Titan's spectrum measured a steep wavelength dependence of the aerosol optical depth (AOD) (Griffith et al., 1991; Gibbard et al., 1999). Tomasko et al. (2005, 2008b) used a detailed analysis of Huygens observational data to constrain the aerosol vertical structure and wavelength dependence of aerosol optical properties including single scattering albedo and AOD. They found that the AOD falls off sharply with increasing wavelength, however the slope of the wavelength dependence softens below 80 km. They also measured the phase functions of the aerosols, which can be used to constrain the particle size. Rannou et al. (2010) used Cassini VIMS data to produce latitudinal gradients of the AOD in the infrared (IR). Lorenz et al. (1997, 1999) used HST to measure hemispheric asymmetry and wavelength variation in Titan's albedo. Significant latitudinal, seasonal, and wavelength dependent variations in the geometric albedo of Titan's haze suggest complex interactions between the aerosols and dynamics. The current hypothesis is that these variations are caused by interactions between aerosol transport by settling and by winds (Toon et al., 1992; Hutzell et al., 1996; Rannou et al., 2002). Essentially, particle sizes are larger when and where upward motions suspend the particles against falling, and smaller when and where downward winds shorten the aerosol lifetime. Tokano et al. (1999) used a three-dimensional model that lacked radiative coupling between aerosol and dynamics to demonstrate the dynamical effect on the aerosols. Rannou et al. (2004) first coupled the 2-D dynamics and microphysics showing that aerosols have a strong influence on dynamics. Furthermore, they were able to show that dynamics were important for creating the detached haze layer. However, their model does not reproduce the full latitudinal extent or seasonal cycle of the detached layer.

1.2. Previous modeling efforts

Toon et al. (1992) described a Titan version of the Community Aerosol and Radiation Model for Atmospheres (CARMA), a cloud microphysics and aerosol model (Toon et al., 1988). This model solves the continuity equations for different sized aerosols at each time step and grid point taking into consideration coagulation, vertical fall velocities and sedimentation as well as other processes such as condensation growth, which are not relevant to tholins. They were able to constrain aerosol parameters such as production rate, radiative properties, and particle charging to calculate particle sizes, fall velocities, and optical depths. However this model did not consider the fractal shape of Titan's aerosol particles. Barth and Toon (2004, 2006) used one-dimensional versions of this code to investigate ethane and methane condensation, precipitation and cloud formation. Lavvas et al. (2010) used a similar 1D model, however with fractal physics, to constrain the microphysical parameters at the Huygens landing site.

Several groups have used GCMs to model Titan's atmosphere and aerosols. Hourdin et al. (1995) were the first to reproduce the superrotating prograde winds. They also showed that the meridional circulation is dominated by pole to pole Hadley cells in the stratosphere, except around the equinoxes when it becomes two equator to pole cells. Tokano et al. (1999) were able to reproduce the temperature gradients and superrotation with a model that included uniform haze opacity, but had to artificially damp the meridional circulation in order to produce anything more than weak superrotation. Rannou et al. (2004) used a two dimensional model, which does not permit the eddies required to produce equatorial superrotation. However, they used the three dimensional model of Hourdin et al. (1995) to parameterize the effects of eddy momentum transport (Luz et al., 2003), and were thus able to produce realistic looking superrotation. Rannou et al. (2004) compared results using a uniform haze layer to those using haze coupled to the radiation and dynamics. In their two dimensional model, they found the aerosols accumulating at the poles radiated in the infrared, enhancing the cooling and increasing the temperature gradient. The increased temperature gradient intensified the zonal winds. However, Rannou et al. (2004) used an aerosol production rate of 1.2×10^{-13} g cm^{-2} s^{-1}, which is about an order of magnitude higher than the consensus from 1-dimensional models (McKay et al., 2001). Recently, Lebonnois et al. (2012a) updated the Rannou et al. (2004) model to 3 dimensions and obtained superrotation. Newman et al. (2011) were also able to reproduce Titan's superrotation by eliminating all imposed horizontal diffusion in the Titan WRF. They identified the upgradient angular momentum transfer required to produce strong equatorial superrotation as being produced by waves, triggered by instabilities at the low-latitude edge of the strong winter hemisphere zonal jet. These waves transported angular momentum in short-lived transfer events, such that zonal winds increased at low latitudes and decreased in winter mid-latitudes (thus re-stabilizing the jet). Although this model includes aerosols in the radiative transfer, it is a simplified scheme. Friedson et al. (2009) produced a three-dimensional model for Titan using the NCAR CAM3 model that includes Saturn's tides and a Cassini based albedo map. However, they were unable to reproduce Titan's superrotation with the CAM model.

In this study, we combined the Titan–CAM and CARMA models to create a new 3D model with the aerosol microphysics coupled to the dynamics and the radiative transfer. We also implemented a fractal treatment of the aerosols analogs similar to Wolf and Toon (2010), which is necessary to accurately represent the particles in Titan's atmosphere. We analyzed the three dimensional aerosol distribution and seasonal variation. Here we present the initial results of this new model. We explore the suite of parameters that give the best fit to the aerosol data, including the vertical profile and wavelength dependence of the AOD, number density, and particle size. We also investigate how the aerosols affect the heating rates, temperature profiles, and albedo on Titan.

2. Model description

2.1. CAM model description

Friedson et al. (2009) adapted the Community Atmospheres Model (CAM3) to Titan. This new model includes a dynamical core, a treatment of the planetary boundary layer (PBL), tidal forces from Saturn, radiation, surface interactions, a photochemistry package, and a microphysical treatment of the aerosols.

The Titan–CAM (Friedson et al., 2009) has a dynamical core that uses a finite volume scheme that does sequential parallelization in 2 directions, latitude $\times$ longitude. The model has 61 vertical levels going from the surface to 0.35 Pa or about 580 km. The finite volume dynamical core in CAM 3 remaps the height of the constant pressure layers after each time step. This remapping may contribute to the momentum conservation issues described in Section 2.1.1. Most simulations were run at a resolution of $10 \times 15°$ in latitude and longitude. This is a coarse grid, but given the large amount of computing power required to simulate Titan's long timescales, it is a necessary choice. We generally have to perform runs that are several hundred Earth years in length and, due to the small size of Titan and the high wind velocities, short time steps are required to maintain stability. Typically, we ran the models for 500 Earth years, or about 17 Titan years. One drawback of the coarse resolution is that the finite volume dynamical core becomes highly dissipative. This likely a contributing reason that the model of Friedson et al. (2009) did not produce strong superrotation. To test this theory, we also ran a simulation at $4 \times 5°$