DETERMING TITAN'S CLOUD ALTITUDE AND OPACITY IN THE CASSINI VIMS DATASET

*P. Corlies[1], A. G. Hayes[1], M. Ádámkovics[2], S. Rodriguez[3], J. Kelland[1], E. Turtle[4], J. Mitchell[5], J.Lora[6], R., the Cassini VIMS Team, *Presenting author (pmc232@cornell.edu), [1]Department of Astronomy, Cornell University, Ithaca NY, [2]Department of Astronomy, University of California Berkeley, Berkeley CA, [3]University of Paris 7, Diderot, Paris France [4]Johns Hopkins Applied Physics Laboratory, Laurel MD, [5]Department of Physics and Engineering, Westmont College, Santa Barbara CA, [6]Department of Earth, Planetary, and Space Science, University of California Los Angeles, California CA

Summary: We present an analysis of 150+ clouds observed by Cassini VIMS in Titan's atmosphere. Results are compared to general circulation model predictions (GCMs).

Introduction: Since the arrival of Cassini to the Saturnian system in 2004, clouds have regularly been observed on Titan [1,2,3,4,5]. We have since learned that clouds are driven by seasonal variations. We also have provided important insights into constraining general circulation models [2,5,6], and provide important context for surface/atmosphere interactions [7].

As the only other body in the solar system with an active hydrologic cycle [8], Titan has clouds that act as the primary observable of the atmosphere and allow for direct measurements of atmospheric phenomena on both short and seasonal timescales and local to global spatial scales.

Because of the complexity of modelling Titan's atmosphere, to date only a handful of clouds have been closely analyzed to determine altitude and opacity [e.g. 4,9]. Here, we present the analysis of an order of magnitude more clouds, allowing, for the first time, global and seasonal dependencies to be inferred.

Methods: Since the first observations of clouds in the late 1990's [1] various techniques have been developed for analyzing clouds on Titan. However, given previously computational expensive retrievals, only a few clouds have been modeled to date. We employ here a recently developed radiative transfer (RT) code for Titan's atmosphere – PyDISORT [10]. This code, built around the discrete ordinates method (DISORT) [11], allows for faster atmospheric retrievals.

Clouds are observable from their increased scatering contribution in Titan's atmospheric windows. To find clouds to analyze, we have systematically gone through the VIMS dataset and compiled a list of observed clouds (see Abstract #2748, this meeting). We then used an average spectrum for each cloud for the analysis.

Clouds can be modelled by inserting an additional layer into the RT model containing the radiative characteristics of the cloud. Free parameters include the cloud's optical depth, altitude, and average drop radius. To simulate self-consistent scattering properties for the cloud layer, Mie scattering is used to determine the single scattering albedo, phase function, and optical depth as a function of wavelength.

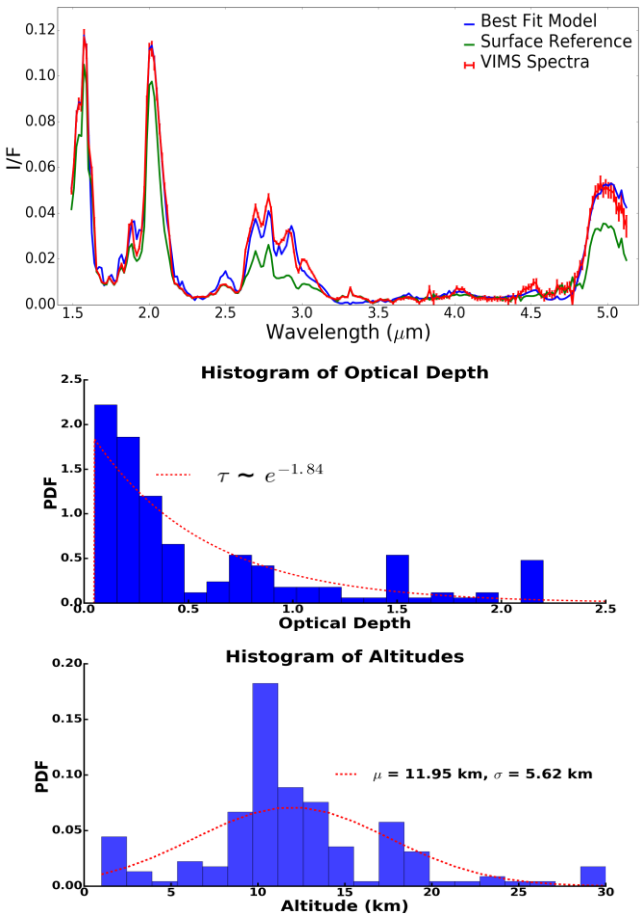

Fig. 1: Top Panel: Example of a best fit cloud spectrum retrieved form the inversion. A surface reference is used to correct for local haze and surface albedo variations. Middle and Bottom Panels: Probability distribution functions (PDF) for cloud parameters from modelling of 150+ clouds observed by VIMS. Average cloud heights sit at 5-15km, in Titan's troposphere. As on Earth, optically thin clouds are more

We employ a combination of systematic and gradient minimization search techniques to quickly and accurately find the best fit parameters for each cloud, which are determined through a minimum chi-squared.

Results and Discussion: For this analysis 150+ clouds have been identified and simulated with an RT model (see Figure 1). Findings show that clouds generally reside at 5-15 km in altitude, which is in

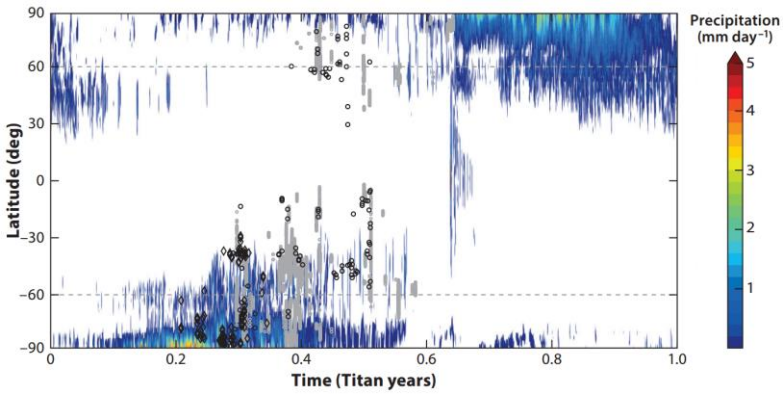

Fig. 2: Figure from [6] demonstrating a comparison of observed clouds (both from the ground and Cassini [4,5]) to simulated precipitation. Idealized GCMs are still yet to fully capture the observed cloud frequency on Titan, but understanding the nature of Titan's clouds will help with future verification of increasingly realistic inputs to GCMs.

agreement with recent modelling efforts [12]. We find no typical average cloud drop radius at wavelengths comparable to the VIMS instrument (1-5 μm) suggesting that drop sizes are large with respect to these wavelengths, resulting in gray scattering. This is consistent with past modelling of clouds on Titan [13]. Finally, optical depth is found to follow a power-law distribution, with more frequent thinner clouds.

There is little seasonal dependence on cloud properties (aside from location), suggesting relatively uniform dynamical evolution of clouds on Titan. Cloud altitudes are in agreement with other modelling efforts, suggesting a relative surface humidity of >~50% when clouds are present [12]. Further analysis of resolved cloud systems can provide insight into local surface humidity and wind patterns.

Understanding cloud properties provides various crucial insights into Titan's hydrology. First, by understanding their location we can better constrain inputs to general circulation models (GCMs), such as volatile transport, that can influence seasonal cloud frequency [14]. To date, GCMs have yet to completely capture the observed cloud distribution, suggesting further dynamics yet to be captured in the models (see Figure 2).

Finally, with the complete identification of clouds in the VIMS dataset, cloud evolution can be tracked and compared to models, providing further insight into mesoscale simulations of Titan's atmosphere. Furthermore, tracking cloud evolution informs the net transport of volatile materials, winds at various altitudes, and potential for precipitation. Such analysis also allows for better understanding of surface/atmospheric interactions such as orgographic clouds (see Figure 3).

References: [1] Griffith C. A. et al. (1998) *Nature, 395,* 575-578. [2] Rodriguez. S. et al. (2011) *Icarus, 216(1),* 89-110. [3] Ádámkovics, M. et al. (2010) *Icarus, 208*¸ 868-877 [4] Turtle E. P. et al. (2011) *GRL, 38,* L03203 [5] Rodriguez S. et al. (2009) *Nature, 459,* 678-682 [6] Mitchell J. L. and Lora J. (2016) *AREPS,* 44, 353-380. [7] Turtle E. P. et al. (2011) *Science, 331,* 1414-1417. [8] Stofan E. R. et al. (2007) *Nature, 445,* 61-64. [9] Griffith C. A. et al. (2009) *APJ 702,* L105-L106. [10] Ádámkovics, M. et al. (2016) *Icarus, 270,* 376-388. [11] Stamnes K. et al. (1988) *Appl. Opt., 27,* 415-419. [12] Rafkin S. C. R. and Barth E. L. (2015) *JGR Planets, 120,* 739-759. [13] Barth E. L. and Rafkin S. C. R. (2007) *GRL, 34,* L03203. [14] Lora J. and Ádámkovics, M (2016) *arXiv:1610.06277v1*

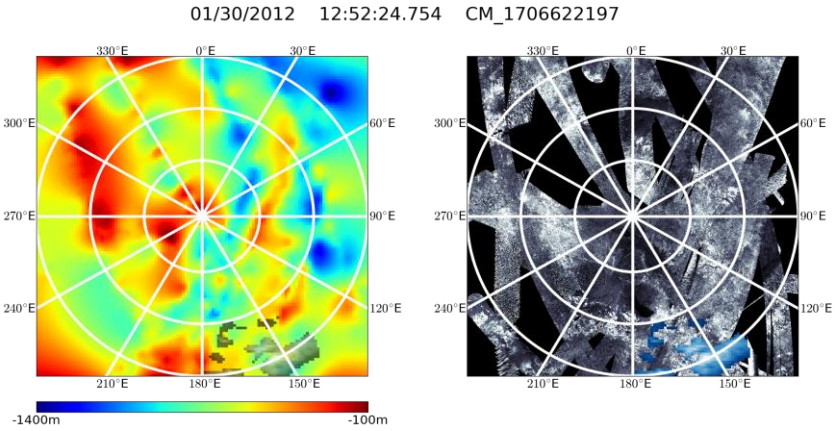

Fig. 3: Left Panel: Updated south polar projection of Titan's topography (see Abstract #2703, this meeting) with a cloud observation overlain. Cloud morphology and evolution suggests possible orographic formation for this system. Right Panel: Same as the left, but with a SAR underlay showing cloud correlations with SAR-bright terrain (identified as mountains).