TRAMS: A new dynamic cloud model for Titan’s methane clouds

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Convective clouds on Titan may play an important role in climate dynamics, atmospheric chemistry, and the overall volatile cycle. To study the formation and evolution of these clouds, we have developed the Titan Regional Atmospheric Modeling System (TRAMS). TRAMS is a three-dimensional, time-dependent, coupled fully compressible dynamic and microphysical model capable of simulating methane and ethane clouds in Titan’s atmosphere. In initial model tests over a two-dimensional domain, a warm bubble or random temperature perturbations trigger a parcel of air to rise. For an initial methane profile with a 60% surface humidity, convection occurs for positive temperature perturbations of 1 K or greater. Cloud tops are between 25 and 35 km, consistent with observations of the south polar clouds. For a drier methane environment in the lower atmosphere, characteristic of the Huygens landing site, convection does not occur, but a layer of stratiform clouds is able to form at altitudes around 10 km. Citation: Barth, E. L., and S. C. R. Rafkin (2007), TRAMS: A new dynamic cloud model for Titan’s methane clouds, Geophys. Res. Lett., 34, L03203, doi:10.1029/2006GL028652.

1. Introduction

Titan’s polar clouds have been a prominent feature in the southern hemisphere for a number of years. Clouds were initially detected through brightness changes across Titan’s disk [Griffith et al., 1998, 2000] and later, with improvements in adaptive optics, imaged through ground-based observing [Roe et al., 2002; Brown et al., 2002]. The Cassini spacecraft and long-term ground-based observations [Schaller et al., 2006] have shown a recent drop in occurrence of these south pole clouds, possibly linked to seasonal changes.

Griffith et al. [2000] argued the clouds they detected were convective in nature due to rapid lifetimes (hours) and common heights (~25 km). For convective clouds to form, a parcel of moist air must rise until reaching saturation at the lifting condensation level (LCL). Further upward forcing of the parcel results in condensation and latent heat release and the parcel will cool at the saturated adiabatic lapse rate. If the environmental lapse rate exceeds the saturated adiabatic lapse rate, and the parcel continues to rise, it will reach a level at which it becomes buoyant relative to its surroundings, the level of free convection (LFC). The parcel can then freely accelerate upwards. Griffith et al. [2000] looked into the stability of Titan’s atmosphere and found an LCL of 2 km and an LFC of 5.5 km for a humidity of 60% at the surface; the LFC is lowered to 2 km for a parcel at 80% humidity.

Awal and Lunine [1994] focused on local convective processes; Voyager only saw the lapse rate in two locations, hence a low probability of being in the region of localized vigorous convection. For surface methane volume mixing ratios within Voyager data error bars (3–7%), they found the areal coverage of moist plumes to be at most 10⁻³, but more likely ~10⁻⁷. Plume velocities resulting in moist convection were ~1–10 m/s depending on surface methane and the environment relative humidity at the parcel’s saturation point.

A recent convection model by Hueso and Sánchez-Lavega [2006] also found strong updrafts of 1–20 m/s are necessary to initiate convection. They developed a 3-D methane convection model to characterize the amount of precipitation produced by storms (composed of methane droplets) at Titan’s South Pole. For methane humidities in the troposphere greater than 80%, they could produce vigorous methane storms which dissipated in 5–8 hrs and left behind more than 100 kg/m² of methane rainfall on the surface.

There are a number of differences between our model and that of Hueso and Sánchez-Lavega [2006]. They employ a different dynamical core which uses the anelastic approximation to the continuity equation. Our model is fully compressible; also we include additional microphysical processes such as nucleation, freezing and melting and a more rigorous treatment of the coalescence of cloud particles as described in Section 2. Nevertheless, we include some comparisons between our model results and theirs in Section 3.

2. Modeling

The Regional Atmospheric Modeling System (RAMS) was developed at Colorado State University in the mid-1980s. The model is a fusion of several terrestrial weather simulation codes [Mahrer and Pielke, 1977; Tripoli and Cotton, 1982; Tremback and Kessler, 1985; Pielke et al., 1992] and has been successfully adapted to study the weather on Mars (Rafkin et al., 2001). RAMS is a fully compressible non-hydrostatic model, which permits the simulation of atmospheric flows with large vertical accelerations, such as convective clouds. The model is three-dimensional, time-dependent, and easily configured over a wide range of user-specified horizontal grid spacings that can range from meters to hundreds of kilometers. The vertical coordinate is a terrain-influenced sigma system that may be geometrically stretched with height to provide highest resolution in the boundary layer.

A coupled dynamic and microphysics model, TitanRAMS (TRAMS), was adapted from RAMS to simulate clouds on Titan. We run the model in 2-D, with 55 to 60 vertical layers up to 50 km and 200 to 400 horizontal layers of 1 km spacing. Vertical grid spacing is 10 s of meters near
3. Results and Discussion

A warm bubble at the surface forces the air parcel to rise. The bubble has a gaussian shape ($\sigma = 4$), vertical size of 200 m, and is centered in $x$. The bubble is perhaps representative of forcing from sensible heat flux, but is not meant to quantify the amount of energy which can reach Titan’s surface.

3.1. Convective Clouds

With the $\text{Lellouch et al. [1989]}$ methane profile (60% surface humidity for pure liquid methane), 1 K bubbles are sufficient to lift the air parcel to the LFC and subsequent latent heating drives convective clouds. Cloud properties (e.g., number of particles, vertical extent, updraft velocities) are independent of bubble temperature; warmer bubbles merely expedite the time to initial condensation. The cloud top between 30 and 35 km is consistent with Figure 1 and cloud heights estimated from observations [e.g., Griffith et al., 2000]. Particle concentration is large ($\sim 1–10 \text{ cm}^{-3}$), with updrafts over 10–20 m/s (Figure 2). Such velocities are consistent with the plume model of Awal and Lunine [1994] and the convection model of Hueso and Sánchez-Lavega [2006]. Increasing the bubble spatial size produces clouds of similar physical properties. These clouds only
Affirmative clouds described above, however particle sizes are similar (mean radius of order 600 μm).

This thin layer of stratiform clouds at the simulated Huygens landing site lack sufficient mass for significant methane rainfall. Even after 8 hours, the amount of methane precipitation at the surface in any given location is less than 10⁻⁸ kg/m². For the 60% surface humidity case (Lellouch model), the large amount of methane in the atmosphere prolongs the storms. The initial cloud has completely dissipated within 5 hours. As the cloud particles are raining out and evaporating near the cloud base, downdrafts produce pools of cold air, triggering additional cloud formation, and the cycle continues throughout the rest of the simulation.

3.3. Rainfall

At the Huygens landing site, there is insufficient energy for convection. Instead, gravity waves triggered by the bubble produce layered (stratiform) clouds near the already saturated layer. Figure 3 shows clouds present near 10 km. Vertical velocities are generally under 10 cm/s. The abundance of cloud particles is much less than the convective clouds described above, however particle sizes are similar (mean radius of order 600 μm).

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Figure 3. Stratiform cloud produced using the methane sounding from the Huygens landing site three hours after initial cloud formation. The cloud is composed entirely of methane-nitrogen droplets; no ice crystals are present. The shaded contours are log₁₀ of the cloud particle number concentration (where N is per cubic centimeter). Contour lines indicate vertical velocity (m/s). Horizontal distance (x-axis) is in kilometers. Altitude is shown only up to 15 km as clouds do not form at higher altitudes for this case.

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in these simulations; neighboring storm circulations interact. Also, the magnitude of the updrafts, typically 10–12 m/s, are ~1/2 of the isolated bubble case. The weaker updrafts further decrease the upper level storm outflow that is necessary to balance the updraft mass flux. As in the warm bubble cases, artificially increasing the coalescence efficiency to 100% vastly increases the surface precipitation. Still, even the standard coalescence formulation can produce upwards of 10 cm of surface precipitation.

[22] Storm life cycles are also markedly different. After one convective cycle, the atmosphere is nearly uniformly depleted of CAPE; no additional storms can develop. Images of Titan’s south polar clouds clearly show numerous storms at any given time. Thus, these storms are likely to behave as the complex of storms simulated with random perturbations. However, the simulations indicate that energy for the storms is depleted within hours, suggesting an efficient convective destabilization mechanism to offset the stabilizing effects of the clouds. On Earth, convective energy is typically resupplied via large-scale circulations, allowing additional convective cycles. Perhaps Titan’s large scale circulation does the same.

4. Summary

[23] We have developed a convection model for Titan with methane cloud microphysics and demonstrated its ability to produce clouds. While the clouds shown in these simulations are triggered by an artificial warm bubble or temperature perturbation, their characteristics are consistent with observations (e.g., cloud top height, large horizontal extent, short lifetimes). The simulations show that despite only small variation in Titan’s temperature profile in the troposphere from equator to pole, the possibilities for convective clouds vary widely as this is tied to the methane profile. Moist environments of ≥50% surface humidity produce strong convective storms with large updraft velocities while a dry environment like the Huygens landing site can only produce thin stratiform clouds. The appearance of clouds at the pole, if they are indeed convective, would then be evidence of a wetter environment than that observed by

[80] A single storm triggered by a warm bubble may not be representative of a broad convectively active environment because a single storm will neither compete with other storms for CAPE nor will it suffer from destructive compensating subsidence generated by neighboring storms. To explore these potential effects, we constructed a simulation 400 km in horizontal extent initialized with random temperature perturbations not to exceed 3 K in magnitude in the lowest few hundred meters superimposed on the Lellouch methane profile. This initialization procedure had the effect of triggering nearly simultaneously numerous convective cells. Using cyclic boundary conditions created an effectively infinite numerical domain such that no storm could escape the effects from its neighbors.

[21] The effect of storm competition is pronounced (Figure 5). While the number concentrations are similar to the convective clouds described in section 3.1, the horizontal extent of the cloud and in particular the cloud anvil is substantially reduced. Upper level storm outflow is impeded by

3.4. Multiple Storms

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the Huygens probe. Future work will involve an analysis of plausible trigger mechanisms, including surface heating, topography and rising motions associated with Titan’s Hadley circulation, and 3-D simulations with winds, as well as the effects of ethane in methane droplets, which is likely to play a significant role in the stability of raindrops near the surface.

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References


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