Abrupt Climate Change on Titan

Jeff Portwood

12 March 2012

1 Introduction

Titan, Saturn's largest moon, contains a "hydrology" of methane cycles between the surface and atmosphere, resulting in cloud formations, precipitation, surface accumulation and presumably runoff [*Turtle et al.*, 2011]. Currently, large hydrocarbon lakes can be found near the poles of Titan, but most of Titan's methane is held in the atmosphere as vapor [*Lorenz et al.*, 2008]. Evidence of a once global distribution of liquid methane is given through Cassini RADAR observations of dry riverbeds at all latitudes of Titan. The current distribution of methane in the upper atmosphere will be lost within 300 million years, as methane is irreversibly transformed into other hydrocarbons [*Pierrehumbert*, 2010]. If this methane sink is not being resupplied by outgassing from Titan's interior then are we seeing Titan transition from a "wet" climate to a "dry" climate?

To address these and other questions, our group, led by Professor Jonathan Mitchell of the University of California Los Angeles, has been investigating the role of methane in Titans climate using numerical simulations. In preliminary work [*Mitchell*, 2008], it was discovered that as the total amount of methane is decreased, Titan undergoes an abrupt climate transition from a cloudy, cool and wet regime to a hot, largely cloud-free and dry regime. Together with Jonathan Mitchell, we propose to explore this climate transition in greater detail using the one-dimensional model framework.

In particular I plan to address the following questions using data collected from a one-dimensional radiative-convective model:

1. Does the one-dimensional model produce the same climate transition seen in the two-dimensional radiative convective model used by *Mitchell* [2008]?

2. If such a climate transition change does occur in the one-dimensional model, can there exist multiple climate equilibria on Titan? Multiple climate equilibria refers to the possibility that Titan may exhibit two stable atmospheric profiles depending on the amounts of methane vapor held in the atmosphere and liquid methane stored on the surface. Areas completely free of surface liquid methane produce a dry climate with warmer surface temperatures while areas with surface liquid methane produce a wet climate with lower surface temperatures, along with periods of convective precipitation.

3. Does the existence of multiple climate equilibria on Titan produce a state of hysteresis? The existence of multiple climate equilibria in the numerical model could illustrate an important phenomenon known as hysteresis where the state in which a system finds itself depends not just on the value of some parameter of the system, but the history of variation of that parameter [*Pierrehumbert*, 2010].

2 Motivation

The motivation behind this research comes from an investigation by *Mitchell* [2008] on Titans methane hydrology and its impact on atmospheric circulation. *Mitchell* [2008] performed two-dimensional radiative-convective simulations with varying amounts of initial methane on the surface in order to explore feedbacks between surface drying, large-scale dynamics, and precipitation. He showed that high amounts of liquid methane on the surface of Titan resulted in a moist regime, with cool surface temperatures. Conversely, he showed that when the methane depth on the surface was significantly reduced a dry regime occurred in which higher surface temperatures occurred.

I will be further analyzing this abrupt change in surface equilibrium using a one-dimensional radiative-convective model. Stepping down on the model hierarchy to a one-dimensional model will provide a better understanding of the radiative processes that may be occurring on Titan, as well as a more controlled look at the thermodynamics responsible for methane evaporation and condensation and how these processes alter Titans heat budget. While the step down in hierarchy takes away from the realism of Titan's atmospheric dynamics (as it does not include horizontal heat transfer and latitudinal redistribution of methane) an immense amount of knowledge of the vertical dynamics associated with Titan can still be gained.

3 Physical Mechanisms

Before the methods of the numerical model are discussed, a background in the basic mechanisms that drive an atmosphere must be established. This section will discuss the various elements that go into driving an atmosphere and how each play a key role in atmospheric dynamics.

The most basic driving force of an atmosphere is radiation. Energy is given to a planet via solar radiation. Temperature gradients develop between the ground and atmosphere, and these gradients in turn drive circulation. The circulation creates turbulent exchange of energy which can then be deposited deeper in the atmosphere by either moist or dry convection in the form of heat and precipitation.

3.1 Gray Gas Approximation Augmented With Shortwave Radiation

The simplest approximation to driving a climate is the gray gas approximation. In this approach we assume that the optical thickness, which is a measure of the transparency of an atmosphere, is independent of wavenumber. We assume then that the temperature of the planet and atmosphere is only a result of the emission of infrared radiation. The resulting radiative transfer equations, called the Schwarzschild equations, are significantly simplified:

$$\frac{dI^+}{d\tau} = -I_+ + \sigma T^4 \qquad (1)$$

$$\frac{dI^-}{d\tau} = -I_- - \sigma T^4 \qquad (2)$$

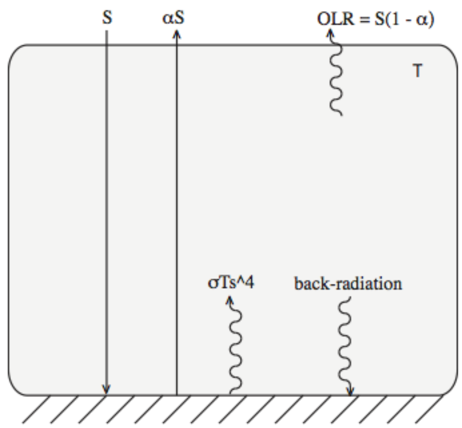

Figure 1: Diagram from *Mitchell* [2008]. The atmosphere is assumed transparent to shortwave radiation. The planetary albedo alpha represents the effects of scattering of shortwave radiation by the atmosphere and reflection by the surface; it is simplest to think of the planetary albedo as being applied to the surface.

where I_+ and I_- are respectively the upward and downward radiation streams, $\sigma \mathrm{T}^4$ is the frequency-integrated Planck function of an air parcel at temperature T, and the optical depth is defined as an increasing function of height.

We next assume that the atmosphere is in infrared radiative equilibrium, creating a temperature profile that monotonically decreases with height. This energy balance can be seen in Figure 1.

Next we will add the effects of shortwave absorption to the model by including the radiative effects of a stratosphere. Rather than allowing the effects of shortwave radiation scattering by the planetary albedo (α) we will let the stratosphere instantaneously reprocess a constant fraction of shortwave radiation into infrared radiation. This allows for shortwave absorption directly in the troposphere.

Finally the effects of dry and moist convection are included into the model and are visualized in Figure 2. Lack of moisture on the surface results in a shallow layer of dry convection occuring near the surface. Dry convection results in an atmospheric temperature profile that follows a dry adiabat, leading to warmer surface temperatures. If liquid is present on the surface, moist convection will dominate the lower atmosphere and produce a temperature profile that follows a moist adiabat. The details of the radiation-convection model and the parameters used can be seen in *Mitchell*

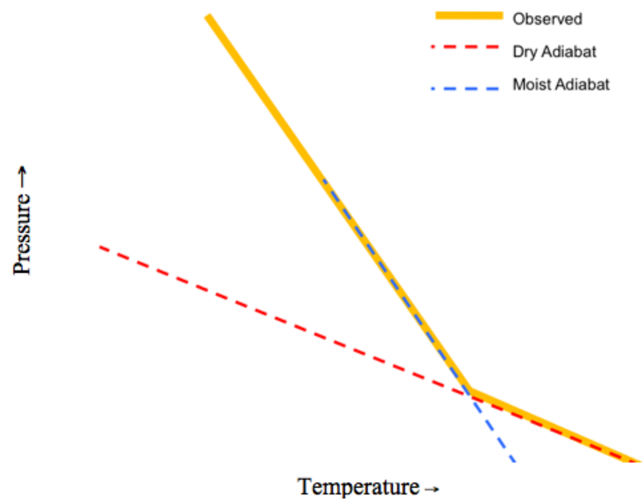

Figure 2: This cartoon atmospheric profile (not to scale) displays the basic, yet powerful dynamics that occur on Titan. The thick orange curve loosely represents the observed temperature profile of Titan from the Huygens probe (not actual data); the dotted blue line represents the methane moist adiabat; and the dotted red line represents the nitrogen dry adiabat.

[2008]. The final radiation-convection model is depicted schematically in Figure 3. The values of the various parameters shown in the figure will be the values used for the numerical model explained in Section 3.

4 Numerical Model Setup and Data Collection Technique

The abrupt climate transition will be studied using a one-dimensional radiative-convective numerical model developed by *Mitchell* [2008] to show the possibility of the existence of multiple climate equilibria on Titan. The model is a one-dimensional simulation that implements a gray radiation scheme and hard convection scheme to drive the dynamics of the simulated Titan atmosphere.

The parameters used to set up the radiation scheme are consistent with the globally averaged vertical fluxes shown in Figure 3:

$\alpha = 0.55$ (albedo)

$\zeta = 0.15$ (fraction of solar beam reprocessed by stratosphere)

$\gamma = 0.35$ (amount of solar flux that is reprocessed by the atmosphere into infrared radiation

All of these parameters will remain constant.

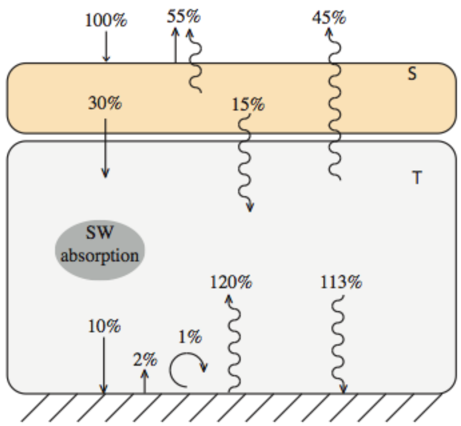

Figure 3: Figure from *Mitchell* [2008]. Schematic of the energy balance for a one dimensional global average radiative-convective model of Titan. Energy fluxes are normalized to the top-of-atmosphere solar radiation. Straight lines indicate shortwave fluxes, wavy lines indicate infrared fluxes, the circle indicates convective fluxes, the gray box is the troposphere, and the orange box is the stratosphere. Titans stratospheric haze prevents 55 percent of the incoming solar radiation from reaching the troposphere. Of the remaining 45 percent of the solar beam, 15 percent is reprocessed by the haze into downwelling infrared radiation, 20 percent is absorbed by constituents in the troposphere, and 10 percent reaches the surface. The surface is near radiative energy balance, allowing only 1 percent of the energy to drive convection. Fluxes represent those produced in the model of *McKay et al.* [1991]

4.1 Numerical Model Setup

Initially the model is given a specified initial surface depth, which represents the amount of liquid methane present on the surface. The model then runs its radiation and convection schemes until the atmosphere has fully equilibrated. To ensure that the model reaches equilibrium the run time used for each simulation is the equivalent of 40 Titan years. During the simulation the radiation and convection schemes extract the liquid methane from the surface via evaporation, causing the surface depth to decrease. The extracted methane is deposited into the atmosphere as methane vapor, causing the atmospheric depth to increase. Depending on the the initial surface depth, the surface will either equilibrate to a dry state, or it will equilibrate to a wet state, due to the removal and addition of methane through evaporation and precipitation. The final surface and atmospheric depths are the parameters that will be the primarily focus for comparing a dry Titan climate with a wet Titan climate.

4.2 Data Collection Technique

Initially the model was given surface methane depth of 1.0 m and left to equilibrate for the equivalent of 40 Titan years. During this equilibration the liquid methane on the surface was evaporated and stored in the atmosphere as vapor, leaving the surface completely dry, undergoing dry convection and thus equilibrating into the dry regime. An additional 1.0 m of liquid methane was added to the surface and again left to equilibrate for another 40 Titan years, where the 1.0 m of liquid on the surface was evaporated and stored in the atmosphere as vapor. Now a total of 2.0 m of methane is present, but it is all stored as vapor in the atmosphere leaving the surface dry.

This process was repeated, adding 1.0 of liquid methane to the surface after each equilibration of the atmosphere. The atmosphere can only hold a finite amount of methane vapor, however, before it begins to deposit excess methane back to the surface via precipitation. It is at this maximum atmospheric depth where the transition occurs to a cool regime dominated by moist convection.

The process was then ran in reverse by giving an initial surface depth of 10.0 m and incrementally taking away 1.0 m of liquid methane from the surface after each equilibration period. The same dynamics occurred, only this time a transition from wet to dry was observed as the reservoir of surface methane was depleted.

5 Results

The first objective in studying the abrupt climate change on Titan was to ensure that the one-dimensional model did indeed produce the abrupt change seen in the two-dimensional model run by *Mitchell* [2008]. The next objective was to adjust the vertical diffusion of methane to better match the results observed by *Mitchell* [2008].

Initially the one-dimensional model was ran with a diffusion parameter of $\nu_v = 0.01$ m$^2/s$ in accordance with *Mitchell* [2008]. The abrupt climate transition did occur, however the transition occurred at surface reservoir depth above 2.0 m and below 3.0 m, a value smaller than expected. The transition is depicted in Figure 4 and shows that the dry regime equilibrated to a surface temperature of $\sim$ 92 K, lower than the dry surface temperature observed by *Mitchell* [2008], and that the wet regime equilibrated to a surface temperature of $\sim$ 91 K, higher than the wet surface temperature in *Mitchell* [2008]. The discontinuities in surface temperature equilibria between the one-dimensional and two-dimensional models are most likely due to the inability of the one-dimensional model to account for horizontal heat transport and methane distribution, as the two-dimensional model is a global average. Further analysis showed that the atmosphere was only able to hold $\sim$ 2.75 m of methane vapor, meaning any initial surface reservoir greater than this value resulted in the wet regime. Figure 4 shows this transition occurs in the process of adding liquid methane to the surface as well as in the process of extracting liquid methane from the surface. Both perturbations produce a transition at the same atmospheric depth value.

After verifying that the one-dimensional model produced an abrupt transition with lower surface temperature equilibria than *Mitchell* [2008], that vertical diffusion parameter was increased in order to allow more methane to be vertically distributed in the atmosphere. Figure 5 shows the results of a vertical diffusion parameter of $\nu_v = 1.00$ m$^2/s$, 100 times the inital value. By increasing the vertical diffusion the level of atmospheric storage is increased, and more of the initial surface reservoir can

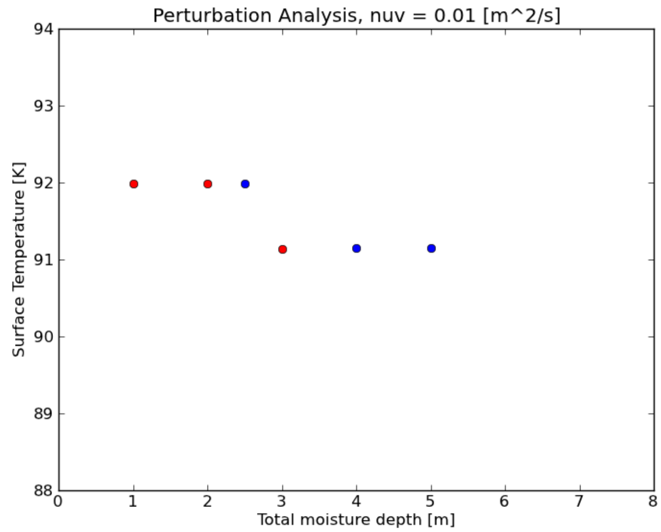

Figure 4: Equilibrium surface temperatures with initial surface moisture depths. Red dots indicate the positive perturbation (where methane was added to the surface) and can be viewed from left to right. Blue dots indicate the negative perturbation (where methane was removed from the surface) and can be viewed from right to left.

be evaporated and stored in the atmosphere. This allowed for the transition from the dry to wet regimes (or vice versa) to occur at higher initial reservoir depths. Whereas the atmosphere previous held $\sim$ 2.75 m of methane, the increased diffusion allowed the atmosphere to store $\sim$ 4 m. The increased diffusion rate also raised surface temperatures for both the dry and wet equilibria to $\sim$ 93 K and $\sim$ 91.5 K respectively.

6 Future Objectives

The future objectives for my research will be further analyzing the abrupt climate transition talked about in Section 5. These objectives include:

1. Updating the numerical model to try and improve the discontinuities of the surface temperature plots between the one-dimensional and two-dimensional models.
2. Exploring the possibility of hysteresis resulting from initial reservoir depths.

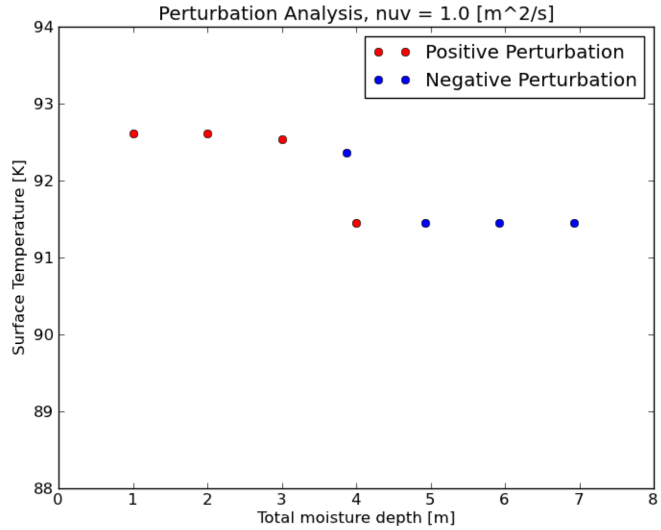

Figure 5: Equilibrium surface temperatures with initial surface moisture depths. Same color scheme as in Figure 4.

6.1 Updating Numerical Model

There are a variety of parameters that can be altered in the numerical model that may help account for the differences in surface temperatures between the one-dimensional and two-dimensional models.The effects of vertical diffusion have already been discussed in Section 5, however, the effects of the boundary layer have yet to be observed. In the two-dimensional model of *Mitchell* [2008], the boundary layer was set to 1000 mbar. In the one-dimensional model the boundary layer was set to the top of atmosphere, essentially removing it altogether, because a large gradient formed in the lower atmosphere where relative humidity decreased from 100

6.2 Hysteresis

The existence of multiple climate equilibria in the numerical model could illustrate an important phenomenon known as hysteresis where the state in which a system finds itself depends not just on the value of some parameter of the system, but the history of variation of that parameter [*Pierrehumbert*, 2010]. As discussed in the previous sections, the perturbation model showed that when starting at a low initial surface reservoir, and perturbing the reservoir in small increments, an equilibrium surface temperature transition occurs. Also described were the effects of starting the model at a much higher initial surface reservoir and perturbing it in the opposite direction by decreasing the reservoir in small increments. As of now the transition from wet to dry and from dry to wet occur at the same depth, but if the perturbation analyses show an equilibrium surface temperature transition at a different depth values, then the model will be in a state of hysteresis.

The existence of hysteresis associated with Titan could greatly enhance the study of its atmosphere and help determine what kind of atmospheric state Titan currently is exhibiting.

7 Conclusion

Much has been learned of the effects that surface methane depth has on Titan's climate. We've shown that by incrementally decreasing initial surface methane depths, surface drying occurred which a caused the lower layers of the atmosphere to undergo dry convection and warm surface temperatures. Conversely, we showed that incrementally increasing initial surface methane depths led to moist convection and an abrupt transition back to cooler surface temperatures.

Abrupt climate changes occurred when the initial surface depth equalled the level at which the atmosphere can store a majority of the surface methane as vapor. The level of atmospheric storage was increased by increasing the vertical diffusion parameter, ν_v. For $\nu_v = 0.01$ m^2/s the level of atmospheric storage was ~ 2.75 m. Meaning an initial surface reservoir greater (less) than 2.75 m resulted in a wet (dry) climate with a surface temperature of 92 K (91 K). Bumping up the vertical diffusion 100 fold to $\nu_v = 1.0$ m^2/s led to an increased atmospheric storage value of 4 m and increased surface temperature extrema of 91.5 K and 92.5 K.

While the differences in surface temperature of the wet and dry regimes are only on the order of 1 K for the two vertical diffusion cases, the abrupt transition is clearly seen by the one-dimensional model. More analysis on this transition needs to be done with one-dimensional model such as introducing a more realistic boundary layer. There is no evidence yet for hysteresis, but testing this hypothesis on the two-dimensional model may produce different results.

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