The Dynamics Behind Titan's Methane Clouds

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- Abbreviations: MMC – Mean Meridional Circulation; SSS – Southern Summer Solstice; SAE – Southern Autumnal Equinox; GCM – General Circulation Model; ITCZ – Intertropical Convergence Zone; LSC – Large-Scale Condensation

Abstract

We present results of an axisymmetric global circulation model of Titan with a simplified suite of atmospheric physics forced by seasonally varying insolation. The recent discovery of midlatitude tropospheric clouds on Titan has caused much excitement about the roles of surface sources of methane and the global circulation in forming clouds. While localized surface sources, such as methane geysers or "cryovolcanoes", have been invoked to explain these clouds, we find in this work that clouds appear in regions of convergence by the mean meridional circulation and over the poles during solstices, where the solar forcing reaches its seasonal maximum. Other regions are inhibited from forming clouds due to dynamical transports of methane and strong subsidence. We find that for a variety of moist regimes, i.e. with the effect of methane thermodynamics included, the observed cloud features can be explained by the large-scale dynamics of the atmosphere. Clouds at the solsticial pole are found to be a robust feature of Titan's dynamics, while isolated midlatitude clouds are present exclusively in a variety of moist dynamical regimes. In all cases, even without including methane thermodynamics, our model ceases to produce polar clouds around 4-6 terrestrial years after solstices.

1 Introduction

Methane clouds were first observed in Titan's troposphere as occasional brightening in disk-averaged infrared photometry[1]. Clouds were observed in the southern hemisphere later during southern spring[2]. In 2001, clouds were observed near the south pole, presumably due to strong solar heating at the pole just preceeding Southern Summer Solstice (SSS, which occurred in October 2002)[3, 4]. The first observations of midlatitude clouds following SSS were reported in 2005[5], and were confirmed by Cassini observations[6, 7] at a time when Titan is progressing towards Southern Autumnal Equinox (SAE). Efforts have been focused on explaining what controls the position of clouds and mechanisms that set the timing of observed shifts in their positions. Earth-based observations show midlatitude clouds preferentially form at a particular latitude and longitude, which suggests they owe their existence to localized surface sources of methane[8]. But, the longitudinal distribution of clouds is more uniform if both ground-based and Cassini data are taken into account[7]. It is known from ground-based observations that large outbursts in cloud activity occasionally occur[9]. Ground-based observations from late 2005 revealed that Titan's south polar clouds, the most persistent cloud features, have completely dissipated, and concurrently the sporadic activity at midlatitudes first subsided and then re-established at lower latitudes[10].*

The position, variability and seasonality of clouds is certainly, in some manner, influenced by the seasonally varying distribution of solar heating. However, a local radiative-convective model with no large scale dynamics will produce convection at essentially all latitudes.† On Earth the pattern of tropical convection is strongly modulated by large scale dynamics. In particular, moisture converged by the large-scale dynamics condenses out within the upward branch of the mean meridional circulation (MMC), releasing latent heat there. This tends to narrow and strengthen the updraft and produce persistent clouds and precipitation in a region known as the Intertropical Convergence Zone (ITCZ). The upward flow in the ITCZ is balanced by large areas of subsiding dry air that suppress convection and diverge moisture at the surface, which produce the sub-tropical deserts[11]. There is every reason to believe that dynamics have an equally profound effect on convection and cloud formation on Titan since methane plays an equivalent role to water vapor in Earth's climate. Because of its slow rotation rate (1/16 of Earth's rotation rate), theory predicts Titan's MMC should extend to the poles, and temperatures should be roughly uniform across the region of overturning[12]; this is born out by the weak equator-to-pole surface temperature gradient observed by Voyager[13]. Titan, in effect, is an "all tropics" planet, and we are justified in interpreting, at least some level, cloud patterns in the framework of existing theories of tropical dynamics.

Titan's season is about 30 Earth years long; since SSS was in 2002, SAE will not happen until late 2009. Until recently, the latitudinal positions of midlatitude clouds seemed not to change significantly with seasonal shifts in maximum solar heating, at least for the last few years during which disk-resolved observations are available[8]. Modeling studies of the response of Titan's troposphere to seasonally varying forcing could shed light on the mechanisms controlling seasonal cloud patterns. GCMs of Titan to date have mainly focused on stratospheric dynamics. The stratosphere of Titan is super-rotating (global angular momentum exceeds solid-body rotation) and contains a thick organic "haze" which shrouds the lower atmosphere. Stratospheric zonal wind velocities

*These observations were published *after* the initial submission of this paper.

†See supporting materials for figures of these simulations.

over the equator are 100 m/s, and the midlatitude jets reach $\simeq$150+ m/s[14]. GCMs with Titan's rotation rate have shown that eddies converge momentum towards the equator to sustain super-rotating winds[15, 16, 17, 18]; this mechanism was first proposed to explain super-rotating winds on Venus[19]. Simulations with coupled interaction between the dynamics of the stratosphere and the organic haze production and distribution can reproduce the seasonality of latitudinal contrasts in haze thickness, which explains the polar "hooding" seen in observations[6, 20, 21, 22].

The discovery of tropospheric methane clouds in the midlatitudes of the summer hemisphere makes a strong case for a detailed study of the response of tropospheric dynamics to seasonal forcing. Indeed, interest in modeling Titan's troposphere is on the rise. A recent GCM simulation was able to reproduce the basic features of current cloud patterns; in that model, clouds are produced through methane transports by the MMC and symmetric eddies. This study predicted clouds at both poles at all seasons and midlatitude clouds in both hemispheres around both solstices and in general showed extremely weak seasonality[23]. Another modeling study of Titan's troposphere focused on the latent feedback of methane condensation during different seasons, but did not account for the full seasonal cycle[24]. The meteorological impact of surface types, primarily surface thermal inertia, has also been explored in a GCM; this study primarily addressed seasonal changes in surface temperatures, but also concluded the distribution of observed cloud features is consistent with a solid surface with low thermal inertia[25]. A GCM simulation was also used to predict balloon trajectories for a proposed mission to Titan[26]. The basic behavior of the tropospheric system, though, has hardly been explored, and in particular the relevant timescales in the system require further study.

The radiative damping time of Titan's troposphere is very long, similar in magnitude to the Titan season. It might be expected, therefore, that seasonality in Titan's tropospheric circulation and precipitation would be significantly attenuated. However, since there is no global ocean on Titan[27] the surface presumably has quite low thermal inertia. Furthermore since the tropics (which span the globe of Titan) are thermally uniform, small perturbations in surface temperature from changes in the surface energy balance can have very dramatic effects on the position of convection.[‡] Since Titan's surface has very low heat capacity, we expect it to respond quickly to changes in solar forcing if the atmosphere is unable to communicate its heat capacity to the surface; the warmest surface temperatures will be found at the subsolar point in this case, and the pattern of convection/precipitation will follow along in-phase. Or if the atmosphere is able to communicate its large heat capacity to the surface by some mechanism, we expect the seasonal cycle of convection/precipitation to be somewhat attenuated.

Radiative and turbulent (sensible and latent) energy fluxes at the surface couple the surface and the atmosphere. Here we provide estimates of these energy fluxes for Titan's surface. The solar forcing at Titan is only a few W/m^2, and the atmosphere and surface at ~100 K only emit 5-6 W/m^2 of thermal radiation. The available flux of latent energy at the surface can be estimated by an assumed turbulent mass flux[§] times the mixing ratio of the condensible times its latent heat of vaporization. By this estimate, the available latent energy flux at Titan's surface is 10^2 to 10^3 W/m^2. By the bulk formula, sensible heat flux is generally quite weak compared to the latent heat flux. In summary, latent fluxes have the potential to greatly exceed other energy fluxes, though they will be restricted by energy balance. We might expect, therefore, that the seasonal cycle of convection/precipitation will be sensitive to changes is surface latent flux since this has the greatest potential to couple the low-thermal-inertia surface to the high-thermal-inertia atmosphere.

Our goal is to provide a simple modeling framework that will allow us to constrain the physical mechanisms affecting the seasonal behavior of Titan's clouds. Observations of the surface of Titan have shown vast areas of typical desert morphologies such as dunes and other areas that may be densely populated with lakes of methane.[¶] As noted previously, there is no evidence for a global ocean. In the present study we explore the effect various levels of methane concentrations in the troposphere, as modified by methane convection and the supply of methane from the surface, have on the dynamics of the troposphere. We find that a simple gray radiation scheme is able to reproduce the important features of the observed temperature profile (see Methods section). Such a computationally efficient scheme allows us to thoroughly explore parameter dependencies of our

[‡]For a description of this effect in the Earth's tropics, see [28].

[§]We estimate the mass flux using the bulk aerodynamic formula $C_d \rho U_0$, where C_d is a roughness factor, ρ is the density of air in the lower atmosphere, and U_0 is a gustiness parameter.

[¶]See public images available at http://saturn.jpl.nasa.gov.

model, and it sets the stage for us to extend our parameter study to three dimensions, which would otherwise be prohibitive due to the computational time required for the full radiation scheme. In the following section, we establish consistency of our model with observations. We then present our model results and offer some conclusions. Those interested in an overview of our model are referred to the Methods section at the end of the paper.

2 Consistency with Observations

Given the recent Cassini/Huygens observations of Titan's troposphere, it is important to establish consistency of our model simulations with the available data. Our dynamical simulations reproduce the observed weak equator-to-pole surface temperature gradient of a few Kelvin. Radiative-convective simulations, in contrast, show a much larger surface temperature gradient of between $10 - 20K$, so the MMC is strongly reorganizing the thermal structure in the troposphere, as expected from theory (see Introduction)[12]. The diagnosed tropospheric vertical temperature profiles in simulations with the effect of methane thermodynamics included are consistent with observations by the Huygens Atmospheric Structure Instrument, while the lapse rate in the dry simulation is generally somewhat higher than is observed[30].

Observations of the shearing of Titan's methane clouds reveal typical zonal wind speeds of $\mathcal{O}[10ms^{-1}]$[6], which are similar to zonal winds produced in our simulations. The Doppler Wind Experiment on the Huygens probe, which descended at around 10^oS latitude, measured easterlies in the boundary layer and weak westerlies aloft[29]. The MMC in our model is able to sustain angular-momentum-conserving zonal winds aloft because the dynamical overturning of our model is short compared to a seasonal cycle and since we have no parameterization for horizontal momentum mixing. There is some question as to whether eddies mix momentum up-gradient and produce super-rotation in the troposphere, as they do in the stratosphere.[‖] We do not attempt to model super-rotation in our current model since tropospheric zonal wind measurements are too sparse to rule out the characteristic uniform angular momentum distribution of a Held-Hou-like MMC[12].

[‖] There is some evidence that zonal winds reach $30ms^{-1}$ at midlatitudes, which is greater than a momentum-conserving gradient wind allows.

Our moist** convection scheme relaxes methane to a specified relative humidity when convectively unstable. We therefore don't expect our diagnosed methane abundances to match observations in general. This is tolerable for our purposes since we do not seek to account for the radiative feedback of methane, and it has been shown that Earth's dynamics are relatively insensitive to the choice of this relative humidity parameter, though it does have an effect on the surface energy budget[31]. Our intermediate-moisture, dynamical simulation best captures the essence of the observed vertical profile of methane abundances at low latitudes during the season when the Huygens probe gathered data[32].

3 Results: Model sensitivity to methane vapor concentration

To study the feedback of methane thermodynamics on Titan's tropospheric dynamics, we performed three simulations with varying amounts of methane vapor (see Methods section for details). Figures 1(a), 1(c) and 1(e) show contour plots of precipitation for our three dynamical simulations over one Titan season with solar forcing at the surface overlaid for reference; we infer clouds in our simulations by the presence of condensation, which always produces precipitation in our convection scheme.†† In Figures 1(b), 1(d) and 1(f) we show averages of southern hemisphere convective temperature and methane concentration tendencies (in K/day and g/kg/day, respectively) for the 10 terrestrial years bracketing SSS, in order to show where convection has the potential for creating clouds. Below we analyze each case in turn within the theoretical framework outlined in the Introduction.

In the dry case, we remove the latent heating effects of methane evaporation/condensation (see Methods section). In this limit, methane is advected by the dynamics and condenses in the atmosphere to produce precipitation without affecting the thermal structure. The dry case should not be thought of as representing an actual planet, but by comparison to moist simulations serves to illustrate the effect of methane thermodynamics on the circulation of the atmosphere. The most

**Here and throughout, we refer to methane vapor (or the methane cycle) in the troposphere as "moisture", in analogy to the cycle of water vapor in the Earth's troposphere.

††Snapshots of the states of our model atmospheres can be found in the supporting materials.

obvious feature in the dry case is that of widespread precipitation in the summer hemisphere, as seen Figure 1(a). Also notice precipitation is in-phase with the solar forcing, so the thermal inertia of the atmosphere is having little damping effect on the seasonal cycle. During solstices, the ITCZ reaches the summer pole and the MMC extends to midlatitudes in the winter hemisphere, and it switches directions with seasons. Figure 1(b) shows the areas of convection are generally shallower than in the moist cases, which is also to be expected in the absence of latent heat effects by methane; the heights associated with the pressure levels at the top of the convection are shallower than the observed convective clouds at midlatitudes[7]. Given the widespread precipitation predicted in the summer hemisphere, the dry case is inconsistent with observations.

The moist case shows a drastically altered precipitation pattern. Dynamics are clearly having a profound effect on convective cloud formation, suppressing convection throughout much of the atmosphere, as can be seen by comparing the dry and moist runs in Figure 1. First, notice the meandering precipitation band that extends from midlatitudes in one hemisphere to the other, and is out-of-phase with the solar forcing. This feature is the ITCZ and marks the point of surface convergence of the MMC and resulting large-scale updraft. The lag in phase is due to the strong thermal coupling of the surface and atmosphere due to surface fluxes which allows the atmosphere to communicate its large thermal inertia to the surface and dampen changes in surface temperatures. The ITCZ reaches its maximum poleward extent around five terrestrial years after solstices. Methane also significantly destabilizes the lower atmosphere towards convection; Figure 2 shows the convection reaches much deeper into the atmosphere in the moist cases vs. the dry cases. The ITCZ appears in Figure 1(d) as the vertical column of convective tendencies centered at 50^o S latitude, and the extended tendencies northward of this column; the smearing in latitude is due to the ITCZ just having reached its southernmost latitude by the end of our the displayed 10 year average. The second precipitation feature is due to a complex of polar convection that is symmetrically distributed in time around solstices and only at the summer pole, as seen in Figure 1(c). Figure 1(d) shows the most persistent strong convection during SSS is directly at the south pole. Such clouds dissipate around 5 years after solstices, about the time the ITCZ halts its march toward the pole. The moist case is found to be consistent with observations.

The intermediate case, in which the boundary layer scheme relaxes the first model layer toward 50% relative humidity and convection can occur in the interior at 40% relative humidity (see Methods section), shows some features of both the dry and moist cases. As in the moist case, Figure 1(e) shows a sparse precipitation pattern; dynamics are having a comparably profound effect on the distribution of clouds. But the ITCZ shows stronger seasonality like the dry case; the ITCZ is now able to reach the pole, and its phase lag with solar forcing is shortened to 2 terrestrial years. The lack of distinct columns of convective perturbations in Figure 1(f) shows the ITCZ and polar convective patterns have become the same feature. The migration of the ITCZ smears out the convective patterns seen in the 10 year average. It is only when the ITCZ reaches the poles that persistent precipitation appears at the summer pole. During this time, variability in the circulation triggers sporadic cloud activity at mid- and high-latitudes, as can be seen by the streaks of precipitation that move equatorward in Figure 1(e). At around 5 years following solstices, polar clouds cease and the ITCZ begins to migrate back toward the equator. The intermediate case is also found to be consistent with observations of clouds. In particular, the migration pattern of precipitation during and after SSS is quite similar to the distribution of observed clouds during this same time[10].

4 Conclusions

We have performed simplified, axisymmetric simulations of the dynamics of Titan's troposphere with realistic seasonal forcing and methane thermodynamics. Polar clouds are found to be a robust feature of Titan's solstices. In all cases presented, polar clouds cease around 4-6 terrestrial years after solstices. Isolated midlatitude clouds near solstices are produced only in simulations with methane thermodynamics included, since in these cases the ITCZ is enhanced and narrowed, methane is converged to the updraft of the MMC at the surface, and broad regions of large-scale subsidence suppress convection over much of the globe. Our model produces a seasonally varying ITCZ that is in-phase with solar forcing in the dry case and out-of-phase with solar forcing when methane thermodynamics is included. We find the magnitude of the seasonal response, measured both as the phase lag and the maximum latitude reached by the ITCZ, is primarily constrained by the amount of methane being supplied from the surface. Latent heat fluxes from evaporation of methane at the surface stiffens the system against seasonal forcing, since the atmosphere is able to effectively communicate its large thermal inertia to the surface. In the absence of latent fluxes, the surface warms instantaneously to solar forcing and communicates this through the troposphere by convection. We conclude that the effect of methane thermodynamics on the large-scale circulation plays a primary role in determining the location and timing of shifts of Titan's methane clouds.

There is current observational evidence that the polar clouds have already ceased[10]. Although somewhat before our simulations predict this to happen, the actual occurrence makes our results compelling since cessation of polar clouds is a robust feature of our model. In the coming years, Cassini and ground-based observations of Titan's clouds will reveal the seasonal response of the midlatitude clouds. We predict that these clouds will move noticeably in the next 5-7 years if sufficient methane is available at lower latitudes. Future observations by the Cassini mission might also allow us to constrain the distribution of surface sources of methane, which could still be playing a role in determining the observed cloud features.

5 Methods

We use an axisymmetric dynamical core that solves the primitive equations on a regular grid in the latitude-height plane. In our current model we ignore horizontal mixing of heat, moisture, and momentum by eddies. We use a simplified suite of atmospheric physics including the following: 1) gray infrared radiation by a uniformly mixed absorber, neglecting methane radiative feedback, 2) a simplified Betts-Miller moist convection scheme that relaxes to specified relative humidity when unstable for our moist simulations, 3) a bulk aerodynamic surface flux scheme which relaxes methane in the first atmospheric layer toward a specified relative humidity that is calculated in comparison to saturation at the surface temperature and assuming a fixed wind speed, 4) vertical mixing in the boundary layer with a fixed diffusion coefficient and fixed layer depth (1500-1250 mbar), and 5) a simple slab surface with specified heat capacity. We choose to ignore the radiative feedback of methane in order to study the effect of methane thermodynamics in a clean manner. We also choose to ignore any shortwave absorption in the interior, which primarily occurs in the stratospheric tholin haze, since we are concerned with the troposphere which contains most of the mass of the atmosphere. Gray radiation allows for computation efficiency, and gray radiative equilibrium for a well-mixed absorber was found to reproduce the essential features of the observed temperature profile in the troposphere. Although radiative equilibrium can account for the observed temperature lapse rate at Titan's low latitudes (between -1.0 and 0.0 K/km in the lowest 50 km)[30, 33] the (methane) moist adiabatic lapse rate (∼-0.7 K/km) is similar to the lapse rate of the radiative equilibrium state in the troposphere (-0.9 to -0.5 K/km). Given the few single-latitude observations of the temperature structure in the troposphere[35, 30], methane thermodynamics could still be playing an important role in determining the state of the troposphere. We also apply a numerical smoother in the horizontal to the meridional velocities; the operator is equivalent to a second-order diffusion. The smoothing filters out much of the variability of the 2D dynamical core, which results from symmetric instability. These simplifications allow us to model the overall character of the large-scale circulation in a reasonable amount of computational time.

In all simulations, we fix the total infrared optical depth, τ_∞, to the frequency-averaged value obtained by a full Titan radiative transfer model: $\tau_\infty \simeq 3.33$[33]. We performed three dynamical simulations intended to represent the spectrum from dry to moist (methane thermodynamics included) dynamical regimes. We performed a "dry", dynamical simulation by setting the latent heat of vaporization to a very small number in our convection and boundary layer schemes; while this approach does not formally converge to dry adiabatic adjustment, we have confirmed the results are qualitatively and quantitatively similar to using a hard adiabatic adjustment scheme. The advantage of this approach is that it allows us to prognose precipitation without including the thermodynamic feedback of methane condensation and evaporation. We also performed two "moist" simulations, one in which the boundary layer scheme relaxes the lowest layer of the atmosphere toward saturation and requires a large relative humidity for convection to occur in the interior (80%), and one which relaxes the lowest model layer moisture toward intermediate levels (50%) and requires less humidity for the convection to occur (40%). We refer the reader to Table 1 for a summary of our model runs. Since we do not include a cloud parameterization, we use condensation/precipitation as a proxy for cloud formation.

Since the amount of methane that is supplied from the surface is controlled by a separate parameter in our boundary layer scheme, the primary mechanism controlling the surface energy budget is somewhat ambiguous between the convection scheme and the turbulent surface flux scheme since both can influence humidity in the lowest model layer. It is important to resolve this degeneracy since it is the surface fluxes that couple the surface and atmosphere, and ultimately determine the dominant thermal reservoir (either the surface or the atmosphere, see Introduction) which controls the seasonal response of the circulation. We have performed sensitivity tests of these parameters to explore their relative contributions to the surface energy budget and how changes in them affect the seasonality of the circulation. We find that the seasonal response of the circulation is relatively insensitive to the convection scheme relative humidity parameter, but it is strongly sensitive to the boundary layer scheme relative humidity parameter; the brevity of this article precludes presentation of all these simulations. Furthermore, our calculations show that for simulations with large-scale condensation (LSC) only, that is without a convection scheme, much of the character of the seasonal response is maintained, albeit with considerably more variability since LSC produces bursty precipitation events (see Figure 2).

One might question why we choose to employ a moist convection scheme rather than simply assuming precipitation occurs when and where a gridbox becomes saturated, i.e. LSC. Figure 2 shows the prognosed precipitation pattern in our model with LSC rather than the convection scheme, with the results of our moist case (with the convection scheme) overlaid for reference. It is clear the two approaches give qualitatively similar results, but the LSC scheme produces more bursty precipitation events which adds considerable variability to the system. Observations of Titan's methane clouds do show variability, with dramatic outburst events[9] and noticeable gaps in cloud formation[10], which might lead to the conclusion that methane condensation in Titan's atmosphere is LSC-like. But the variability of an LSC scheme is sensitive to resolution, which makes it difficult to argue the observed variability owes its existence to the variability of an LSC scheme at a given resolution. Furthermore, the scale of convective turbulence is well below that of any GCM grid scale, and the resolved convection in a hydrostatic model is very inefficient at transporting heat and moisture, making a sub-gridscale parameterization of convection a necessity. Very detailed observations of cloud lifecycles will be required to better understand the nature of methane convection on Titan, and what scheme can best represent it in modeling studies.

Table 1: Summary of parameter settings and results for our model runs. The first two columns represent the value of relative humidity the convection scheme and boundary layer scheme attempt to relax towards, respectively. The third column indicates whether the latent effects of methane condensation and evaporation were included, which represents the primary distinction between"dry" and "moist" or "intermediate" models. The last column represents our judgement as to whether the results are consistent with available cloud observations. "LSC" refers to a simulation run with large-scale condensation only, i.e. without a convection scheme. Radiative-convective simulations are presented in the supporting documents.

Model	Convection Humidity Parameter	Boundary Layer Humidity Parameter	Latent Effects Included	Consistent with Observations
Rad.-Conv., Dry	80%	100%	No	No
Rad.-Conv., Moist	80%	100%	Yes	No
Dyn., Dry	80%	100%	No	No
Dyn., Moist	80%	100%	Yes	Yes
Dyn., Intermediate	40%	50%	Yes	Yes
Dyn., Moist LSC	100%	100%	Yes	Maybe

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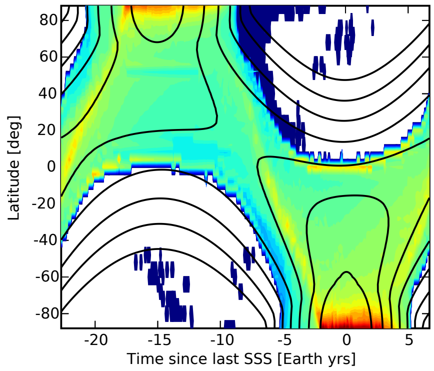
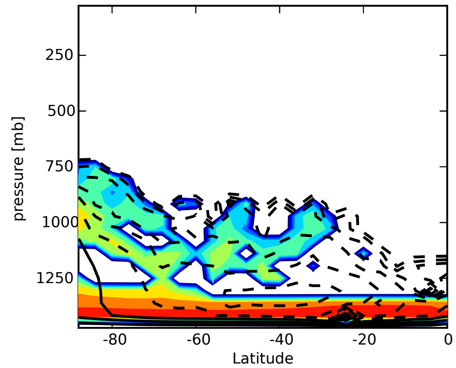
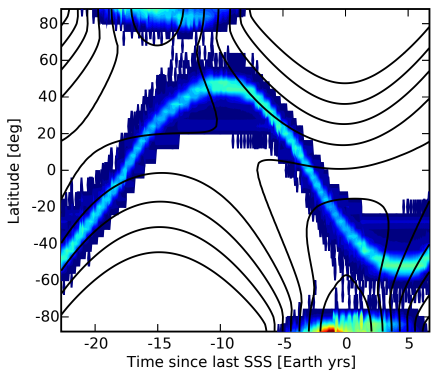


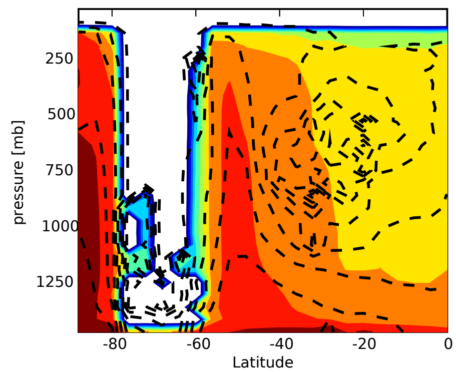
(a) Dry seasonality



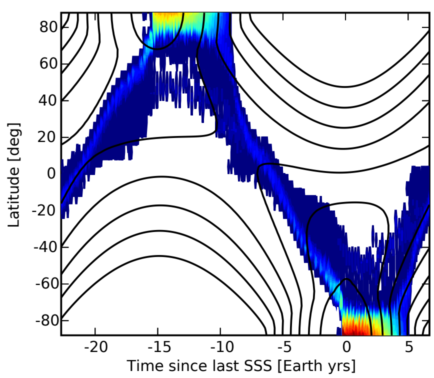
(b) Dry convection



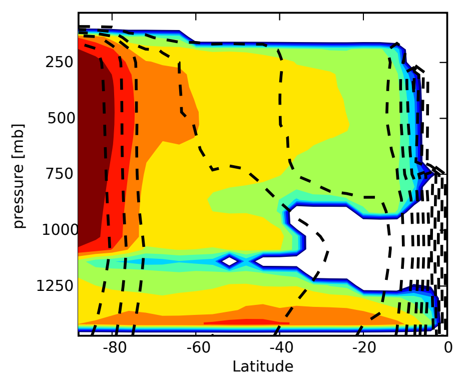
(c) Moist seasonality



(d) Moist convection



(e) Intermediate seasonality



(f) Intermediate convection

Figure 1: Left column: Contour plots of precipitation (filled contours) for our three simulations, with the pattern of solar forcing at the surface overlaid (black lines) for reference. Right column: Contour plots of the logarithm of the averages of convective perturbations for the 10 terrestrial years bracketing southern summer solstice; filled contours are the convective heating rate in K/day on the same color scale (10^{-6}: cool colors to $10^{-1.5}$: warm colors) and dashed contours are the convective drying rate in g/kg/day. “Stepping” patterns at the edges of contours are representative of the resolution of our simulations.

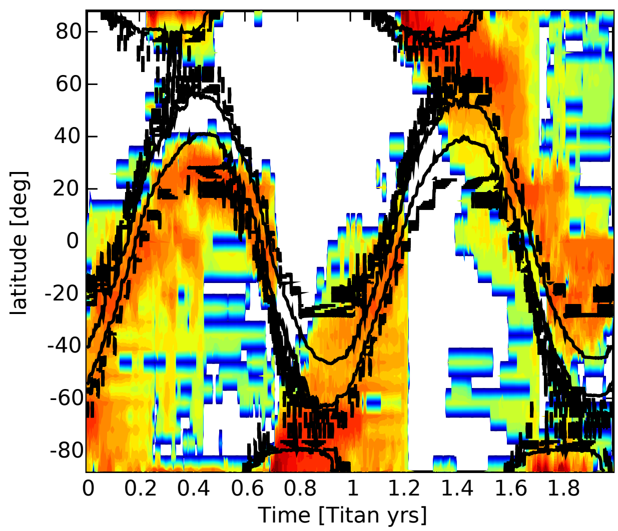


Figure 2: A comparison of precipitation patterns over two Titan seasons for our moist run (black contours) and a run with large-scale condensation (LSC, color contours) only, i.e. no convection scheme.