

TITAN'S TRANSPORT-DRIVEN METHANE CYCLE

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 Received 2012 June 22; accepted 2012 August 2; published 2012 August 17

ABSTRACT

The mechanisms behind the occurrence of large cloud outbursts and precipitation on Titan have been disputed. A global- and annual-mean estimate of surface fluxes indicated only 1% of the insolation, or $\sim 0.04 \text{ W m}^{-2}$, is exchanged as sensible and/or latent fluxes. Since these fluxes are responsible for driving atmospheric convection, it has been argued that moist convection should be quite rare and precipitation even rarer, even if evaporation globally dominates the surface-atmosphere energy exchange. In contrast, climate simulations indicate substantial cloud formation and/or precipitation. We argue that the top-of-atmosphere (TOA) radiative imbalance is diagnostic of horizontal heat transport by Titan's atmosphere, and thus constrains the strength of the methane cycle. Simple calculations show the TOA radiative imbalance is $\sim 0.5\text{--}1 \text{ W m}^{-2}$ in Titan's equatorial region, which implies 2–3 MW of latitudinal heat transport by the atmosphere. Our simulation of Titan's climate suggests this transport may occur primarily as latent heat, with net evaporation at the equator and net accumulation at higher latitudes. Thus, the methane cycle could be 10–20 times previous estimates. Opposing seasonal transport at solstices, compensation by sensible heat transport, and focusing of precipitation by large-scale dynamics could further enhance the local, instantaneous strength of Titan's methane cycle by a factor of several. A limited supply of surface liquids in regions of large surface radiative imbalance may throttle the methane cycle, and if so, we predict more frequent large storms over the lakes district during Titan's northern summer.

Key words: planets and satellites: atmospheres – planets and satellites: individual (Titan)

Online-only material: color figures

1. ATMOSPHERIC ENERGETICS

Titan's transport-dominated methane cycle is fundamentally distinct from the hydrological cycle of Earth's tropical zone. Earth's hydrology is primarily driven by local radiative imbalance at the surface that amounts to $\sim 115 \text{ W m}^{-2}$ of evaporation occurring over the tropics. An additional $\sim 40 \text{ W m}^{-2}$ of evaporation results from horizontal heat transport away from the equator by the motion of the atmosphere-ocean system (Trenberth & Stepaniak 2003a). Following conventions from the literature on Earth's climate energetics (Trenberth & Stepaniak 2003a), we identify the role of energy transport by the atmosphere in a simulation of Titan's climate and global circulation (Mitchell et al. 2011). Vertically integrated quantities are defined $\tilde{M} = \int_0^\infty \rho M dz = (1/g) \int_0^{P_s} M dp$. The total energy of the atmosphere, after vertical integration, is

$$A_E = \tilde{k} + c_p \tilde{T} + \tilde{\Phi}_s + \tilde{L}q \quad (1)$$

$$\approx D_E + L_E = M_E, \quad (2)$$

with kinetic energy $K_E = \tilde{k}$ (assumed to be negligible), internal energy $c_p \tilde{T}$, potential energy $\tilde{\Phi}_s$ (which combine to give dry-static energy $D_E = c_p \tilde{T} + \tilde{\Phi}_s$), and latent energy $L_E = \tilde{L}q$. The atmospheric energy is very nearly equivalent to the vertical integral of the moist-static energy, $M_E = D_E + L_E = \tilde{h}$, with $h = c_p T + gz + Lq$.

The thermodynamic equation,

$$\frac{\partial D_E}{\partial t} = -\nabla \cdot \mathbf{F}_{D_E} + Q_1, \quad (3)$$

and the moisture equation,

$$\frac{\partial L_E}{\partial t} = -\nabla \cdot \mathbf{F}_{L_E} - Q_2, \quad (4)$$

combine to give the moist-static energy equation,

$$\frac{\partial M_E}{\partial t} = -\nabla \cdot \mathbf{F}_{M_E} + Q_1 - Q_2, \quad (5)$$

where

$$\mathbf{F}_{D_E} = \widetilde{\mathbf{v}c_p T} + \widetilde{\mathbf{v}\Phi} \quad (6)$$

$$\mathbf{F}_{L_E} = \widetilde{\mathbf{v}Lq} \quad (7)$$

$$\mathbf{F}_{M_E} = \mathbf{F}_{D_E} + \mathbf{F}_{L_E} \quad (8)$$

$$Q_2 = L(\tilde{P} - \tilde{E}) \quad (9)$$

$$Q_1 = R_T - R_s + H_s + L\tilde{P} \quad (10)$$

$$= R_T + F_s + Q_2. \quad (11)$$

Q_1 is the column-integrated diabatic heating in W m^{-2} . Atmospheric heating can arise from radiative imbalances at the top-of-atmosphere (TOA), R_T , and surface, R_s , from surface sensible heat fluxes, H_s , or the release of latent heat by precipitation, $L\tilde{P}$. The column-integrated latent heating, Q_2 , is the difference of precipitation and evaporation, $L(\tilde{P} - \tilde{E})$.

In a steady state, there is a balance between column heating, $Q_1 - Q_2$, and horizontal divergence of moist-static energy, $\nabla \cdot \mathbf{F}_{M_E}$. In an atmosphere with no horizontal heat transport (as is true in single-column, radiative-convective models), this balance reduces to $Q_1 = Q_2$, which further reduces to $F_s = R_T$

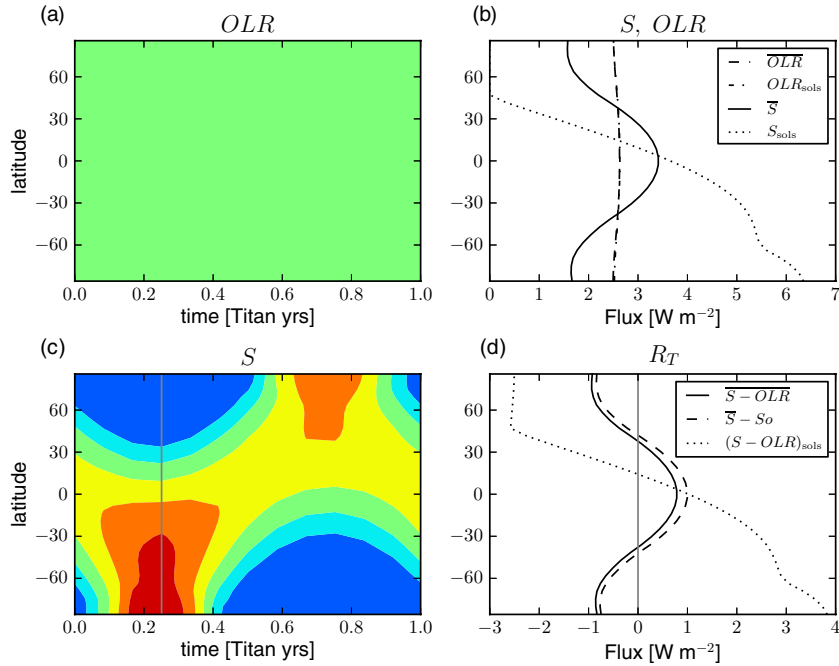


Figure 1. Titan’s top-of-atmosphere (TOA) radiative fluxes are shown separately as outgoing longwave radiation (OLR) and insolation (S) as a function of seasons in (a) and (c) on the same color scale, and as annual means or instantaneously as indicated in (b) and (c). Titan’s OLR (a) is nearly independent of latitude and time, while the insolation (c) varies substantially with season. In the annual mean, insolation is strongly peaked at and symmetric about the equator (solid line). Since the OLR is flat, there is a net imbalance in TOA radiation (c), with $\sim 0.3 \text{ W m}^{-2}$ of heating at the equator and $\sim 0.5 \text{ W m}^{-2}$ cooling at high latitudes. The insolation at the southern summer solstice (dotted line) peaks at the summer pole and gives rise to a net TOA imbalance of up to 2 W m^{-2} .

(A color version of this figure is available in the online journal.)

if the atmosphere does not store heat. In this case, the net surface flux $F_s = LE_s + H_s - R_s$ is equal and opposite to the TOA radiative imbalance $R_T = S - \text{OLR}$, i.e., a heat source/sink at the top of the column must be offset locally by a sink/source at the bottom.¹ Global equilibrium requires the average of R_T to be zero, therefore on average the surface radiative imbalance R_s is offset locally by turbulent exchange of latent heat LE_s and sensible heat H_s with the atmosphere. Based on these arguments, a one-dimensional radiative–convective model of Titan with $R_s \simeq 0.04 \text{ W m}^{-2}$ (McKay et al. 1991) is often invoked as a constraint on the evaporative surface flux, $LE_s \leq R_s$, a severe limitation on the strength of Titan’s methane cycle (Griffith et al. 2008). We argue that horizontal heat transport by the atmosphere may dramatically increase this limit.

2. A SIMPLE ESTIMATE OF TITAN’S EQUATORIAL DRYING RATE

In order to derive a constraint on the strength of Titan’s methane cycle in the presence of meridional heat transport by the atmosphere, first we observe Titan’s outgoing longwave radiation (OLR) is essentially “flat” (independent of latitude) and “steady” (independent of time; Li et al. 2011, Figure 1(a)). Time-independence results from the long radiative cooling time of Titan’s middle troposphere, where the atmosphere radiates to space. However, long thermal times do not account for a flat OLR. Indeed without atmospheric heat transport, Titan’s OLR would exactly balance the annual-mean insolation which is strongly peaked at the equator and decreases poleward (Figure 1(b), solid line). Instead, Titan’s flat OLR (Figures 1(a)

and (b)) is direct evidence for poleward energy transport by the atmosphere (Figure 2). Since the insolation S is a function of both space and time and we require global energy balance on long timescales (i.e., constant A_E), the TOA radiative imbalance $R_T \approx S - S_o$ with S_o the global- and time-mean insolation (Figure 1(d), dashed line). In this case, R_T is offset either by surface energy storage or by horizontal transport of moist-static energy. The former option is ruled out by the solid, low-heat-capacity surface of Titan which prevents energy from being transported or stored for long periods. Thus, we infer a divergent flux of moist-static energy from regions of positive R_T to regions of negative R_T (Figures 1(d) and 2(b)).

The implied heat flux from R_T is in general a combination of latent and dry-static energy (Figure 2), however, we argue the imbalance itself provides a rough estimate of the magnitude of column cooling by latent heat transport out of the tropics (the “drying rate” due to evaporation),

$$Q_2 \sim L\tilde{E} \sim 0.5 \left(\frac{E}{7 \text{ cm yr}^{-1}} \right) \text{ W m}^{-2}, \quad (12)$$

which is in fact the value obtained in our simulation (Figure 2(f)).

Our arguments thus far are based on the assumptions of TOA radiative imbalance, surface energy balance, and the dominance of poleward latent heat transport. Further insight into Titan’s methane cycle can be gained through global circulation model simulations. In the annual mean, the atmospheric heat transport implied by the TOA radiative imbalance is from the equator to higher latitudes. However, simulations (Rannou et al. 2006; Mitchell 2008; Mitchell et al. 2006, 2009, 2011; Schneider et al. 2012) and cloud observations (Brown et al. 2010; Rodriguez et al. 2011; Turtle et al. 2011a) indicate the transport seasonally reverses from a globally northward phase to a southward phase,

¹ Our definition of S is the net solar flux and includes the reduction due to local albedo.

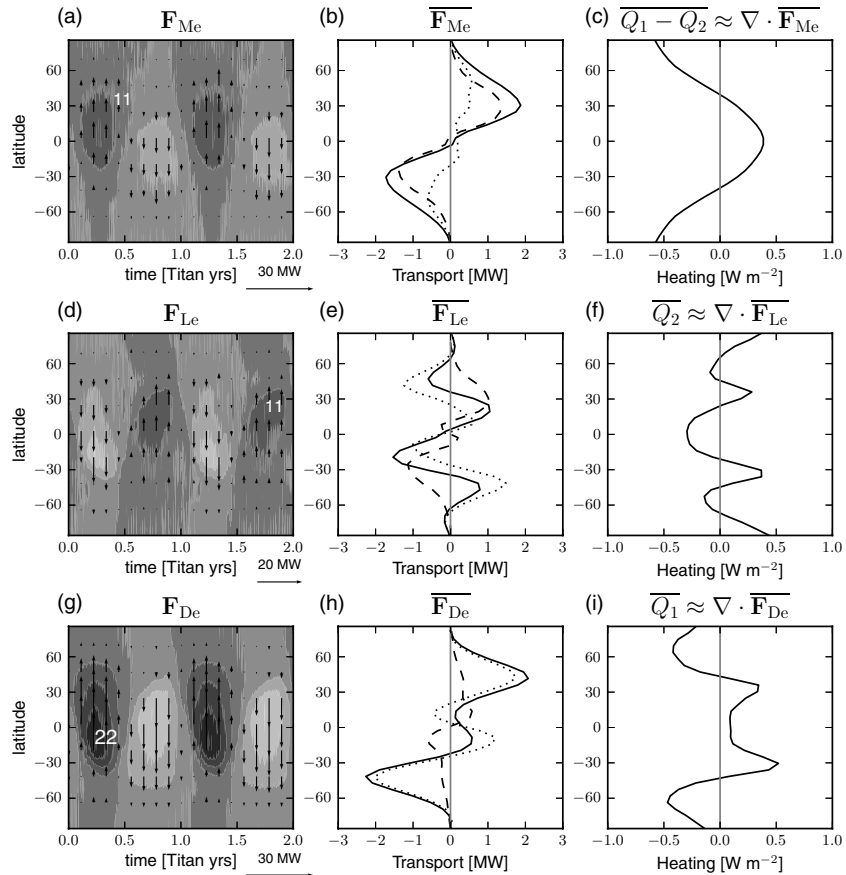


Figure 2. Our model of Titan’s climate as a function of latitude and season (a) indicates peak transport of 11 MW. In the annual mean (b) the transport needed is ~ 2 MW to offset the TOA radiative imbalance (c and Figure 1). Time-dependent (dashed line in b) and mean (dotted line) transport both contribute to the moist-static energy transport. The latent heat transport (d) peaks after solstices at 11 MW, and is offset by dry-static energy transport (g) in the opposing direction. The total moist-static energy transport in the equatorial region (b) is dominated by latent heat transport (e) while dry-static transport is nearly negligible. Divergent latent energy transport in the equatorial region (e) is balanced by net evaporation near the equator and accumulation in mid-latitudes (f).

with large cancellation between the two phases in the annual mean. A compensation between dry-static and latent transports may further enhance the strength of Titan’s methane cycle, as we now demonstrate.

3. TITAN CLIMATE MODEL ENERGETICS

In the remainder of this paper, we substantiate the above arguments and draw attention to differences between Titan’s methane cycle and Earth’s hydrological cycle by comparing GCM simulations of Titan with NCEP reanalysis (Kalnay et al. 1996) for Earth. We focus our attention on a “moist” version of Titan, i.e., one with an unlimited and pure supply of surface methane, in order to establish the potential strength of the methane cycle. We then discuss the effects that a limited surface supply and the presence of liquid hydrocarbon mixtures would have on our results.

3.1. Atmospheric Energetics

Figure 2 shows a breakdown of the energetics of our GCM simulation of Titan reported in Mitchell et al. (2011). The flux of moist-static energy seasonally reverses with peak magnitudes of ~ 11 W m^{-2} (Figure 2(a)). In the annual mean, there is flux divergence at the equator and convergence in mid-latitudes, with peak fluxes of ~ 2 MW (2b). The annual-mean net column heating $\overline{Q_1 - Q_2}$ (top-right panel) is positive at the equator and

negative at high latitudes, indicating an excess of ~ 0.5 W m^{-2} insolation at the equator and an excess of >0.5 W m^{-2} OLR near the poles. The divergence of moist-static energy offsets the net column heating.

At this point, we encounter the first feature of Titan’s climate that distinguishes it from Earth’s tropical climate. When we break the components of the moist-static energy transport into latent (Figures 2(d)–(f)) and dry-static (Figures 2(g)–(i)) transport, we find that the annual-mean heat flux divergence at low latitudes is dominated by latent energy fluxes. As a result, the equatorial region experiences net drying (negative $\overline{Q_2}$; Figure 2(f)) of ~ 0.5 W m^{-2} , while mid-latitudes have net accumulation of a similar magnitude, an effect already documented in several Titan climate models (Rannou et al. 2006; Mitchell 2008; Mitchell et al. 2006, 2009, 2011; Schneider et al. 2012). This confirms our earlier assumption that the magnitude of the equatorial drying rate is set by the horizontal latent energy transport required to keep Titan’s OLR “flat.”

A second distinguishing feature of Titan’s climate follows by dividing the annual-mean latent energy transport into components due to the time mean and variations as $L_E = \overline{L_E} + L'_E$, such that for the case of $\overline{F_{Le}} = L\overline{v\tilde{q}} + L\overline{v'q'}$, we find that the majority of the energy transport occurs due to the time-dependent seasonal cycle ($L\overline{v'q'}$; dashed line in Figure 2(e)) rather than the annual-mean component ($L\overline{v\tilde{q}}$; dotted line). In fact, the

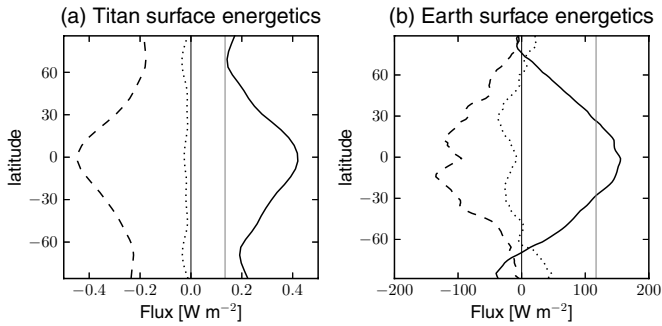


Figure 3. Annual-mean net surface radiative fluxes, which are responsible for driving evaporation and convection, for our Titan model with latitudinal heat transport (a, solid line) exceed radiative fluxes in a model without heat transport and forced by the global-mean insolation (thin gray line) by a factor of three. Evaporative cooling (dashed line) is largely responsible for offsetting the radiative imbalance, with dry-static energy fluxes (dotted line) playing a minor role. In contrast, Earth’s surface energetics (b) is dominated by direct solar heating, as is indicated by the net surface radiative imbalance in a model calculation without horizontal heat transport (thin gray line) as compared to the imbalance in NCEP reanalysis (solid line; average of 1948 through 2012 March). Latitudinal transport accounts for a $\sim 30\%$ enhancement in the equatorial surface radiative imbalance. Both sensible (dotted line) and evaporative (dashed line) fluxes act to cool Earth’s surface, except in very high latitudes.

mean component is convergent at the equator, but the seasonal divergence dominates. In Earth’s tropics, by contrast, the atmosphere accomplishes moist-static energy transport primarily by the mean component (Trenberth & Stepaniak 2003b).

Our analysis reveals a third important feature of Titan’s atmospheric energetics: a large compensation between dry-static and latent energy transports during solstitial conditions (Figures 2(a), (d), and (g)). In fact, instantaneous latent energy fluxes oppose the moist-static energy flux (compare Figures 2(a) and (d)), implying that moisture is being fluxed toward the summer pole. Instantaneous dry-static transport from the summer to the winter hemisphere is roughly double the latent transport (Figure 2(g)), and in the annual mean is moderately convergent at the equator (Figure 2(h), solid line). This compensation is also a feature of Earth’s annual-mean tropical circulation (Trenberth & Stepaniak 2003b), but in contrast Earth’s quasi-steady tropical circulation converges moisture to the equator and diverges dry-static energy toward the poles. Based on our simulations, it seems plausible that Titan’s seasonal cycle enhances the instantaneous methane transport and precipitation by at least a factor of five, or ~ 10 MW.

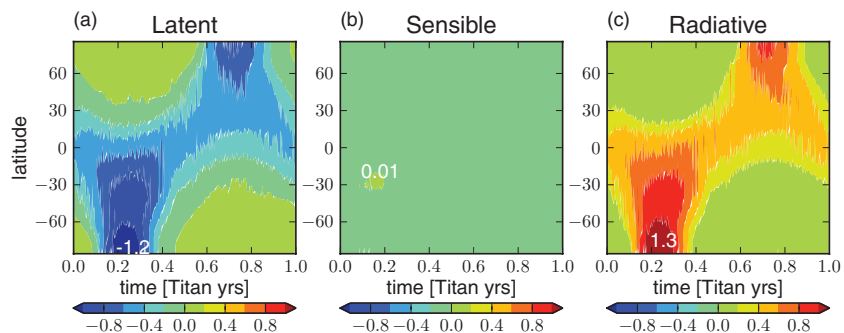


Figure 4. Zonal-mean surface energetics of our model is dominated by a local balance between evaporative cooling (left) and radiative heating (right), with a relatively small role for sensible heat fluxes (center). Local, instantaneous surface radiative imbalance peaks at the summer pole, exactly when the top-of-atmosphere imbalance peaks (Figure 1).

(A color version of this figure is available in the online journal.)

3.2. Surface Energetics

The surface radiative flux imbalance is the energy available to drive turbulent exchange of sensible (dry-static) and latent heat fluxes, and is often cited as an upper limit to the evaporative flux in Titan’s climate system (Griffith et al. 2008; Williams et al. 2012). A comparison between annual-mean surface radiative imbalance (Figure 3) from our “dynamic model” with horizontal heat transport (solid line) and in radiative–convective equilibrium with the annual- and global-mean insolation (thin gray line) demonstrates the influence of atmospheric circulation on Titan’s methane cycle and Earth’s hydrological cycle.² For Titan, the surface radiative imbalance in the dynamic model is larger than the radiative–convective model surface imbalance everywhere. The modeled instantaneous fluxes can be a factor of several larger than this (Figure 4) primarily due to the strong seasonal cycle in the TOA radiative imbalance (Figure 1). By contrast, Earth’s surface radiative imbalance is dominated by “local” heating that does not involve latitudinal heat transport (Figure 3(b), thin gray line). Comparing this with NCEP fluxes, we see that transport accounts for a $\sim 30\%$ enhancement of radiative imbalance at the equator (solid line). This dominance of “local” energetics in Earth’s climate may be the origin of misconceptions about Titan’s climate that lead to large underestimates of the potential strength of the methane cycle. To reiterate, Titan’s “flat” OLR (Figure 1) is direct evidence for 2–3 MW of latitudinal heat transport by the atmosphere (Figure 2(b)), our numerical experiments suggest much of it could be transported as latent energy (Figure 2(e)), and therefore Titan’s methane cycle has the potential to be much stronger than is estimated based on global average surface energetics.

4. IMPLICATIONS AND PREDICTIONS

There are many implications of a more vigorous methane cycle, and here we state two. First, the increased evaporative flux at the surface decreases the residence time for methane cycling through the atmosphere to ~ 75 years rather than a millennium by earlier estimates (Griffith et al. 2008). Similarly, the time between large storm outbursts as reported in Griffith et al. (1998), Schaller et al. (2006), and Turtle et al. (2011b) (with intervals of 9 and 6 years, respectively) can be easily accounted for. If each of these storms produced ~ 1 cm of precipitation over

² In the case of Earth, radiative–convective equilibrium was calculated with a single-column version of the CCM3 model forced by the annual- and global-mean insolation. NCEP reanalysis is used in lieu of a “dynamic model.”

$\sim 500,000 \text{ km}^2$ and thus released $\sim 10^{18} \text{ J}$ of energy (Turtle et al. 2011b), our analysis suggests the time to replenish this amount of methane by evaporation of $\sim 0.5 \text{ W m}^{-2}$ from the surface (the area of Titan $\sim 10^{14} \text{ m}^2$) is less than a day and does not limit the occurrence interval. The same amount of time is required for the atmosphere to cool radiatively following a storm, which is the only path to rid the atmosphere of latent heat released during precipitation. Titan's weak rotation rate allows gravity waves to effectively communicate convective heating through the bulk of the atmosphere, even though convection occurs over a relatively small region. Radiating gravity waves dilute the local heat release from convection by a factor of $\sim 10^{-2}$, the storm area to the total area of Titan. If the global-mean evaporative flux is of order 0.5 W m^{-2} as we have assumed, the long time between observed outbursts suggests they do not contribute significantly to the global- and annual-average precipitation, and that some other process is important for setting their occurrence interval.

A few mechanisms not accounted for in our analysis could throttle Titan's methane cycle. First, and most importantly, there is apparently a limited supply of liquid methane at the surface (Lorenz et al. 2008). Although precipitation does occur in the equatorial region (Turtle et al. 2011b), dry conditions are expected to persist there in the present climate (Rannou et al. 2006; Mitchell 2008; Mitchell et al. 2006, 2009; Schneider et al. 2012), unless methane is currently being resupplied to the low-latitude surface from below (Griffith et al. 2012). Sensitivity experiments with our model demonstrate that as the global methane supply is reduced, the latent heat transport in the equatorial region reduces in-kind and dry-static transport increases to offset the reduction (Mitchell 2008). This effect may partly explain the long interval between large cloud outbursts. Perhaps in the coming northern summer, as the surface radiative imbalance becomes larger over the northern lakes district with abundant surface liquids, there will be much more frequent cloud outbursts than in previous seasons. Second, liquid ethane may well be mixed in liquid methane at the surface, and if so, it would suppress the saturation vapor pressure of methane at a level proportional to the unknown mixing ratio of the two hydrocarbons in surface reservoirs. We tested this effect in our two-dimensional climate simulations by artificially suppressing the evaporation of surface methane (Mitchell et al. 2006, 2009). Our results indicate that while there is a substantial reduction in the annual-mean evaporation rate relative to the "moist" case, the instantaneous latent heat transport at solstices is only reduced by a factor of 2–3, i.e., to 7 MW (Mitchell 2008). Local evaporation and accumulation in the annual mean in this scenario are of order $0.5\text{--}1 \text{ W m}^{-2}$, similar to the "moist" case (Figure 2(f)). Third, Titan's thick atmosphere attenuates the insolation at high latitudes, where beams at a glancing angle experience longer columns (Lora et al. 2011). This effect would reduce the surface radiative imbalance at the summer poles and therefore equally reduce the amount of instantaneous evaporation during the summer solstice (Figure 4). However, since the annual-mean

insolation is peaked at the equator (Figure 3), this effect does not significantly alter our main conclusions.

5. SUMMARY

In summary, Titan's nearly constant OLR, seasonal lower tropospheric circulation, and compensation between dry-static and latent energy transports allow a vigorous methane cycle despite weak, global-mean radiative forcing. Titan's storms are triggered in large-scale updrafts (Mitchell 2008; Mitchell et al. 2006, 2009; Schneider et al. 2012) and waves (Mitchell et al. 2011). Large cloud outbursts (Schaller et al. 2006) and associated precipitation events (Turtle et al. 2009, 2011b) occur as the result of the global transport and focusing power of Titan's atmospheric circulation, with significant implications for the interpretation of surface features ascribed to the presence of flowing and evaporating liquids. The supply of surface liquids in regions of large surface radiative imbalance may throttle the strength of Titan's methane cycle, and if so, we predict more frequent large storms during northern summer.

This work was stimulated by preparation for and discussion during the Titan Through Time 2 workshop at Goddard Space Flight Center held 2012 April 3–5. I am grateful to Rodrigo Caballero and David Neelin for discussions of these topics, and Jeff Portwood for assisting with the one-dimensional, radiative–convective simulation of Earth.

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