Latitudinal Distribution of Ethane Precipitation on Titan Modulated by Topography and Orbital Forcing and Its Implication for Titan’s Surface Evolution

Tetsuya Tokano

Institut für Geophysik und Meteorologie, Universität zu Köln, Albertus-Magnus-Platz, D-50923 Köln, Germany; tokano@geo.uni-koeln.de

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Abstract

A general circulation model with geography constrained by Cassini is used to predict how ethane precipitation in Titan’s lower stratosphere varies with latitude, season, and orbital forcing over the past 100 kyr. Ethane precipitation is generally more prevalent near the winter pole, where stratospheric ethane is transported downward toward the cold trap, and this general pattern is relatively insensitive to orbital parameter variations and geography. However, eccentricity-driven seasonal temperature variations modulate the seasonal asymmetry of ethane precipitation to some extent. The annual ethane precipitation does not monotonically increase from equator to pole but maximizes at selected sites, preferentially over empty deep basins such as Hagal Planitia. Local enhancement of ethane precipitation is caused by katabatic winds from plateau to basin and an associated regional-scale thermally direct circulation over the slope, which induces strong adiabatic cooling near the tropopause. The observed putative ethane clouds off the poles are evidence that ethane condensation is affected by topography. Preferential ethane precipitation over basins may increase the irregularity of Titan’s shape by isostatic crustal subidence after substitution of enclathrated methane by percolated ethane.

Unified Astronomy Thesaurus concepts: Saturnian satellites (1427); Planetary atmospheres (1244); Planetary surfaces (2113)

1. Introduction

One of the boldest predictions concerning Titan’s surface in the post-Voyager and pre-Cassini era was the presence of a kilometer-deep global ocean of ethane (C2H6; Lunine et al. 1983). This prediction was made on the basis of a photochemistry model according to which ethane is the principal product of methane destruction in Titan’s upper atmosphere (Yung et al. 1984). The Huygens probe, as part of the Cassini/Huygens mission, was prepared for possible landing on a hypothetical ethane ocean on Titan. However, the Huygens probe landed on a solid surface (Tomasko et al. 2005), and in other ways as well no global surface ocean was detected by Cassini (West et al. 2005). Deficiencies in early photochemistry models such as the neglect of benzene (Wilson & Atreya 2004; Lavvas et al. 2008; Atreya et al. 2009) or slower downward diffusion of ethane (Atreya et al. 2009) could explain the lack of an ethane ocean. Percolation and sequestration of liquid ethane in the icy regolith is another prominent possibility (Mousis & Schmitt 2008; Choukroun & Sotin 2012). Cassini/Huygens indeed found evidence of liquid ethane below the surface: after landing of the Huygens probe near the equator, traces of C2H6 that evaporated from the surface directly below the probe were detected (Niemann et al. 2010). Ethane was spectroscopically identified in Ontario Lacus, the largest lake in Titan’s southern polar region (Brown et al. 2008). Spectroscopic evidence of ethane in rain was also reported (Dalba et al. 2012).

A quantification of ethane precipitation and its latitudinal distribution is relevant in the discussion of at least the following observations or processes: First, the observed ethane content in the seas/lakes strongly differs between different seas/lakes (Mastrogiuseppe et al. 2018a, 2018b; Mastrogiuseppe 2019). The ethane content in Ontario Lacus near the south pole was found to be higher than in the northern seas. Second, Titan’s excessive polar flattening could have been caused by substitution of CH4 molecules by C2H6 molecules in the clathrate hydrates after percolation of liquid ethane and subsequent isostatic subsidence of the icy crust in the polar region (Choukroun & Sotin 2012).

Ethane condensation and cloud formation in Titan’s lower stratosphere have been simulated by Barth & Toon (2003), Barth & Toon (2006), and Lavvas et al. (2011) using one-dimensional microphysics models for various parameters and in the framework of a two-dimensional global climate model with a built-in microphysics model (Rannou et al. 2006). On the other hand, Graves et al. (2008) simulated the condensation and precipitation of a ternary CH4 − N2 − C2H6 mixture by a one-dimensional microphysics model. The model of Rannou et al. (2006), also used in Griffith et al. (2006), is so far the only one that explicitly predicted (and showed) how ethane precipitation varies with latitude. According to their model, the annual ethane precipitation increases almost monotonically from 10−6 mm per Saturn year at the equator to 0.6 mm per Saturn year, and the latitudinal profile is nearly symmetric about the equator (depicted in Figure 3 of Griffith et al. 2006). This prediction was made under the insolation conditions of the present epoch and assuming a globally uniform surface without topography, etc.

The present study aims at investigating how orbitally forced climate changes (Croll–Milankovitch cycle; Aharonson et al. 2009) and the observed geography of Titan would affect the long-term latitudinal distribution of ethane precipitation on Titan. Previously, both effects were shown to be important for the latitudinal distribution of methane precipitation (Tokano 2019). For practical (computational) reasons, the simulations are confined to the last 100 kyr, which cover a little over two Croll–Milankovitch climate changes.
cycles, and the results of the past 100 kyr are regarded as an example of secular variations that the ethane cycle on Titan may undergo under the present atmospheric pressure and composition.

Section 2 gives a description of the method. Section 3 describes and discusses the predicted ethane cycle in the present epoch. Section 4 presents simulations that are aimed at investigating the impact of the orbital parameters on the ethane cycle. Section 5 discusses the implication of the results for the observations of Titan’s surface and surface liquids.

2. Methods

Ethane condensation in Titan’s atmosphere and its seasonal and long-term variation are predicted by the Cologne (Köln) Titan general circulation model (GCM; e.g., Tokano et al. 2001; Tokano 2019). The Cologne Titan GCM solves the primitive equations on a sphere using a finite-difference dynamical core adopted from the ARIES/GEOS GCM (Suarez & Takacs 1995). The model domain covers the troposphere and stratosphere of Titan up to the 0.01 hPa level (∼400 km). The radiative forcing is calculated with the spectrally resolved radiative transfer model of McKay et al. (1989), which also builds up the vertical distribution of visible and thermal opacity sources. This radiative model takes into account the absorption of solar radiation by the stratospheric haze and gaseous CH₄, absorption by permitted transitions of C₂H₆ and C₂H₂ (acetylene) in the stratosphere, and collision-induced absorption of thermal radiation by various combinations of N₂, CH₄, and H₂. The simulations are run at horizontal grid resolutions of 7°5 (latitude) and 11°25 (longitude). The model domain is represented by 60 vertical layers with grid spacing that gradually increases with altitude. The vertical grid spacing in the lower stratosphere, where ethane condenses, is 3–4 km.

The novel component of the present model version is the ethane cycle. The C₂H₆ mole fraction is introduced as a passive tracer in the GCM and is subject to three-dimensional advection and loss due to condensation. The ethane condensation scheme is greatly simplified relative to previous work (Barth & Toon 2003; Rannou et al. 2006; Lavvas et al. 2011) in that no microphysics model is applied. Instead, C₂H₆ condensation is assumed to occur whenever the instantaneous saturation ratio of C₂H₆ exceeds the critical saturation ratio, i.e., the supersaturation exceeds a certain threshold. The model assumes a critical saturation ratio of 1.36 (relative humidity of 136%) according to laboratory experiments under Titan-like conditions by Curtis et al. (2008). Whenever this occurs, the C₂H₆ abundance in excess of 100% is immediately precipitated out to the surface, i.e., the model assumes no re-evaporation of C₂H₆ in the troposphere. Given this simplification, the predicted C₂H₆ should be regarded as an upper limit.

The model does not contain an explicit chemical source term since ethane production occurs in the upper atmosphere beyond the upper boundary of the model. Instead, the C₂H₆ mole fraction in the uppermost layer of the GCM is prescribed as a function of latitude and season. Hourdin et al. (2004) showed that this approach yields very similar results to a full chemistry transport model. The C₂H₆ mole fraction in the uppermost layer is approximately prescribed considering the observations by the Cassini Composite Infrared Spectrometer (CIRS; Vinatier et al. 2015, 2020; Maltagliati et al. 2015; Teanby et al. 2019; Mathé et al. 2020) as follows:

\[ C_{\text{top}} = \max(1.5 \times 10^{-5}, 1.5 \times 10^{-3}[1 + 2 \cos L_S \sin \phi^3]), \]

where \( L_S \) is the solar longitude of Titan and \( \phi \) is the latitude.

This equation describes that the C₂H₆ mole fraction maximizes at the spring pole at respective vernal equinox, while it is uniform in the entire summer hemisphere. The latitudinal/seasonal variation in C₂H₆ mole fraction at the stratopause observed by Cassini CIRS is not directly incorporated as input data since the Cassini data do not cover a full annual cycle. The abundance of C₂-containing hydrocarbons such as C₂H₆ in the upper atmosphere depends more on transport than on chemistry, so that it shows little dependence on solar activity (Wilson & Atreya 2004). Furthermore, orbital parameter variations do not change the total annual insolation at the top of the atmosphere. Therefore, the boundary condition of Equation (1) is applied to all epochs of the past 100 kyr. Given the error bars of the retrieved ethane mole fraction in the cited publications and incomplete seasonal coverage of the Cassini data considered in constructing Equation (1), a simulation with an alternative upper boundary condition concerning the ethane abundance is also run in the framework of a sensitivity study (Section 3.2). In this case Equation (1) is modified to

\[ C_{\text{top}} = \max(1.0 \times 10^{-5}, 1.0 \times 10^{-5}[1 + \cos L_S \sin \phi^3]). \]

The GCM contains Titan’s geography (topography, thermal emissivity, albedo and thermal inertia) as described by Tokano (2019), but with two updates: First, the surface thermal inertia map is replaced by the recently published map after MacKenzie et al. (2019). According to MacKenzie et al. (2019), the surface thermal inertia varies between 236 J m⁻² K⁻¹ s⁻⁰.⁵ (dunes) and 18,090 J m⁻² K⁻¹ s⁻⁰.⁵ (convective lakes), while in the previous map after Tokano (2019) it varies only between 300 and 800 J m⁻² K⁻¹ s⁻⁰.⁵. All surface parameters are assumed to have been invariant over the past 100 kyr. Second, the topography map after Corlies et al. (2017) provided with a resolution of 0°25 latitude/longitude is smoothed by taking an average over the GCM grid spacing. Titan’s topography map is subject to a relatively large error bar (up to 273 m) because large portions of the map were obtained by interpolation from data along the Cassini RADAR swaths (Corlies et al. 2017). Particularly large uncertainties exist near 30°N/300°W, 35°S/280°W and 35°N/80°W. To test the sensitivity of the simulation to this uncertainty, an additional simulation with an alternative topography map consistent with the error bars is carried out as well (Section 3.2). In this case (here referred to as the minimum topography), the spatially varying error bar of elevation after Corlies et al. (2017) is subtracted from the baseline topography (Figure 1(b)). This decreases the absolute topography by 25–272 m depending on geographic location. The relative topography changes accordingly, particularly in the southern hemisphere. For comparison, a simulation without all these geographic variations is also run for the present epoch.

The evolution of the ethane cycle over the past 100 kyr is simulated by 21 simulations with a GCM covering epochs ranging from the present back to 100 kyr BP (before present) with an interval of 5 kyr. The procedure of the simulation is analogous to previous time-slice experiments (Tokano 2017, 2019). The orbital parameters of the past 100 kyr are adopted from Figure 1 of Lora et al. (2014).
which selected meteorological variables are shown in Figure 7. Corlies et al. obtained by subtracting the spatially varying error bar after Figure 1 spacing topography map after Corlies et al. Global topography maps used in the simulations. The baseline function is larger in the stratosphere owing to condensation at the cold trap. The ethane mole fraction near the stratopause winter stratosphere below 250 km, but there is a strong accumulation vertical gradient in the lower stratosphere. The ethane mole fraction is modest. Once a single meridional cell covers the entire globe in late northern spring (Figure 3(c)), this circulation pattern persists until mid–northern summer (Figure 3(f)). The ethane mole fraction near the south pole increases owing to long-lasting downward ethane transport during southern fall and winter (Figures 2(c)–(g)). An isolated area of enhanced ethane abundance appears near the south pole at 100–120 km in late southern winter when the meridional circulation pattern starts to reverse near the south pole and thereby stops the downward ethane transport. The reversal of the meridional circulation around the northern summer solstice (LS = 177°, Figure 3(b)) reverses the vertical wind direction in either hemisphere and thereby induces an opposite vertical ethane transport, i.e., downward near the north pole and upward near the south pole.

In the present epoch the ethane transport by the meridional circulation is stronger in northern winter than in northern summer because the differential heating is stronger owing to closeness to perihelion. This results in higher ethane abundance in the lower stratosphere (below 150 km) near the north pole in northern winter (Figure 2(m)) compared to the south pole in southern winter (Figure 2(g)). The shallow cross-equatorial meridional cell with an opposite circulation sense near the upper boundary that appears in some seasons (Figures 3(c)–(g) and (k)–(m)) is likely to be an artificial boundary effect since the model does not extend into the upper atmosphere. Thus, horizontal mixing of ethane abundance in the upper stratosphere could be somewhat excessive in this model.

Figure 4 depicts the global distribution of ethane relative humidity in various seasons. Since the relative humidity suddenly drops to 100% after condensation, the average relative humidity is lower than 136% (critical saturation ratio) even in areas of condensation. Ethane condensation occurs within the altitude range 55–60 km, where the average ethane supersaturation becomes largest. This cold trap for ethane is located ~10 km above the tropopause, where the temperature stratosphere and thereby decreases the ethane mole fraction at higher altitudes. The steep change of the stream function between 50 and 60 km is associated with the steep vertical gradient in ethane mole fraction by ethane condensation.

Around the northern vernal equinox (LS = 3°, Figure 3(a)) the meridional circulation is largely symmetric about the equator, with upwelling at low latitudes and downwelling at high latitudes in either hemisphere. Consequently, ethane is transported downward in the polar region, especially near the north pole, where the major ethane source is located in this season. This increases the stratospheric ethane mole fraction near the north pole in almost the entire stratosphere (Figure 2(a)). In early northern spring (Figures 3(b)–(c)) the southern meridional cell gradually expands northward, so that the convergence zone with upwelling gradually shifts northward and eventually reaches the north polar region before solstice (Figure 3(d)). The area of downward ethane transport in the northern hemisphere becomes narrower and eventually disappears in late spring. The reversal of the circulation pattern in this season stops increasing the ethane mole fraction near the north pole and instead decreases it owing to upward transport of ethane-poor air from the troposphere (Figures 2(c)–(d)). On the other hand, the area of downwelling extends to the entire southern hemisphere (southern fall), which begins to increase the ethane mole fraction near the south pole. However, since the ethane source is yet weak in this season, the variation in ethane mole fraction is modest. The ethane mole fraction near the south pole in almost the entire stratosphere could be somewhat excessive in this model.

3. Ethane Cycle in the Present Epoch

3.1. Predicted Ethane Cycle

As a first step, the ethane cycle in the present epoch is simulated. Figure 2 shows how the global distribution of ethane mole fraction changes with season. The predicted ethane distribution is a result of an interplay of sources at the upper boundary, redistribution in the entire stratosphere by the meridional circulation, and condensational sink in the lower stratosphere, which all undergo seasonal variations. The ethane distribution is relatively uniform in large portions of the upper stratosphere below 250 km, but there is a strong accumulation near the stratopause winter/spring pole and a steep vertical gradient in the lower stratosphere. The ethane mole fraction globally decreases from 80 to 50 km by four orders of magnitude owing to condensation at the cold trap.

The global pattern of ethane transport by the mean meridional circulation can be visualized by the ethane stream function (Figure 3). While the mass stream function peaks in the lower troposphere where the pressure is highest, the ethane stream function is larger in the stratosphere (above 50 km) because of the higher ethane abundance there. The meridional circulation in the stratosphere consists of a single large cell that extends from pole to pole. The circulation reverses semiannually around the equinoxes, during which two meridional cells coexist side by side. Unlike the wave-driven Brewer–Dobson circulation in Earth’s stratosphere (Butchart 2014), Titan’s stratospheric meridional circulation is thermally direct circulation and reverses nearly in phase with the tropospheric Hadley-like meridional circulation. Ethane is transported along these streamlines in a clockwise or anticlockwise sense as indicated by the arrows. As a general rule, downward circulation increases the ethane abundance at lower altitudes since the ethane source is located at the top, while upward circulation carries ethane-poor air to the troposphere and thereby decreases the ethane mole fraction at higher altitudes. The steep change of the stream function between 50 and 60 km is associated with the steep vertical gradient in ethane mole fraction by ethane condensation.

Figure 1. Global topography maps used in the simulations. The baseline topography map after Corlies et al. (2017) is averaged over the GCM grid spacing (7.5° latitude, 11.25° longitude). The minimum topography map is obtained by subtracting the spatially varying error bar after Figure 1(d) of Corlies et al. (2017). The vertical line at 348.75° indicates the meridian for which selected meteorological variables are shown in Figure 7.
The lapse rate is large and descending air experiences strong cooling upon approaching the tropopause.

The major cause of ethane supersaturation and subsequent condensation is strong downward transport of ethane-rich air toward the cold trap. Therefore, the winter/spring pole is the primary area where ethane condensation is to be expected on Titan. The simulation, however, predicts a more complex picture. The location and size of the area of supersaturation strongly vary with season. In early northern spring (Figures 4(a)–(b)) supersaturation is found at either pole and near the equator, in late northern spring (Figure 4(c)–(d)) supersaturation occurs only near the south pole, widespread supersaturation is found in late northern summer (Figures 4(g)–(h)), generally little supersaturation occurs in late northern fall (Figures 4(i)–(k)), and supersaturation becomes again more prevalent in northern winter (Figures 4(m)–(n)).

Due to seasonally asymmetric temperature variations, the global distribution of supersaturation is far from being seasonally symmetric, in contrast to the ethane abundance (Figure 2).

Figure 2. Global distribution of C2H6 mole fraction in different seasons in the baseline simulations. Results are shown for 14 seasons that are equidistantly separated from each other by 50 Titan days.
makes it necessary to regard the relationship between ethane transport, temperature, and condensation at the condensation level in more detail. Figure 5 shows how the predicted temperature, vertical wind, and C$_2$H$_6$ mole fraction at 57 km altitude, as well as surface ethane precipitation rate, change with season and latitude. At this level there is a permanent equator-to-pole temperature contrast of less than 1 K (Figure 5(a)). The temperature globally varies with season by $\sim$2 K, with a maximum around the northern vernal equinox ($L_S = 0^\circ$) and minimum around the northern autumnal equinox ($L_S = 180^\circ$). This temperature variation is caused by the eccentricity-driven seasonal variation in heliocentric distance, and the temperature maximum and minimum occur approximately one season after perihelion ($L_S = 276^\circ$) and aphelion ($L_S = 96^\circ$), respectively. This delay is due to the radiative time constant of $\sim$6 yr in this altitude range.

Figure 3. Ethane stream function representing the ethane transport pattern and strength by the mean meridional circulation in the baseline simulation. Positive values correspond to clockwise circulation. The stream function is averaged over 10 Titan days and all longitudes. The arrows indicate the vertical direction of ethane transport.
The mean vertical wind (Figure 5(b)) as part of the stratospheric meridional circulation is of the order of $10^{-5}$ m s$^{-1}$ at the ethane condensation level. Most parts of the spring/summer hemisphere experience upward wind, while most parts of the fall/winter hemisphere experience downward wind. On the other hand, the vertical wind near the equator is always upward. The vertical wind in the polar region is predominantly downward, but it turns to upward around the summer solstice. The vertical wind speed generally increases from low to high latitudes, upward wind maximizes at the summer solstice, and downward wind maximizes at the winter solstice. It exhibits a seasonal asymmetry in that the upward wind in southern summer and downward wind in northern winter are stronger than the upward wind in northern summer and downward wind in southern winter.

The seasonal variation in the C$_2$H$_6$ mole fraction near the condensation level (Figure 5(c)) is fundamentally different.
from that in the upper stratosphere because it is strongly affected by condensation in addition to latitudinal-vertical transport. To a first order the C$_2$H$_6$ mole fraction changes in phase with the temperature because it controls the saturation vapor pressure. Hence, the ethane abundance globally maximizes ($\sim 2 \times 10^{-6}$) near the northern vernal equinox ($L_S = 0^\circ$) and minimizes ($\sim 10^{-6}$) near the northern autumnal equinox ($L_S = 180^\circ$). In addition, the C$_2$H$_6$ mole fraction varies owing to changing vertical winds. The fall/winter hemisphere tends to be more ethane enriched than the opposite hemisphere because ethane-rich air is transported downward from the upper stratosphere.

Ethane condensation/precipitation (Figure 5(d)) undergoes a clear seasonal cycle and strongly depends on latitude. In seasons with globally decreasing temperature ($L_S = 0^\circ$–180$^\circ$), widespread ethane condensation occurs in either hemisphere, but preferentially in the southern hemisphere (fall and winter), where ethane is continuously supplied from the upper stratosphere by downward wind in these seasons. In seasons with globally increasing temperature ($L_S = 180^\circ$–360$^\circ$), ethane precipitation is mostly confined to the northern hemisphere, where downward ethane transport takes place. Ethane condensation almost ceases in the southern hemisphere in these seasons because of increasing saturation vapor pressure of C$_2$H$_6$ and upward transport of ethane-poor air. Equatorial ethane precipitation mainly occurs during the eccentricity-driven cooling in northern spring.

In addition to these general seasonal and hemispheric trends, perennial latitudinal maxima can be recognized at 60$^\circ$–50$^\circ$, 40$^\circ$–50$^\circ$, and 70$^\circ$–80$^\circ$ N. The ethane precipitation rate in these areas exceeds $\sim 10^{-8}$ mm day$^{-1}$, while elsewhere it is one to two orders of magnitude smaller. For comparison, the results obtained from the simulation with globally uniform geography are shown in Figure 6. In this hypothetical case the strongest vertical wind and lowest temperatures are found right at the poles. This causes the ethane precipitation rate to peak at the poles as well.

Understanding the qualitative difference in the precipitation pattern between the simulations with and without topography requires a closer look at the relationship between circulation, temperature, and ethane humidity in the vicinity of large
topographic features. Figure 7(a) shows, as an example, the meridional circulation along the 348.75°W meridian that contains large topography variations. This meridian crosses Rossak Planitia Basin near the south pole, the dark region Mezzorania, Hagal Planitia Basin (at this longitude down to −940 m) near 55°S, a plateau (150 m, 40°S) inside the bright region Tsegihi, equatorial dunes, relatively flat northern hemisphere, and Punga Mare near the north pole. The long south-facing slope between the plateau in Tsegihi (30°S) and Hagal Planitia Basin (60°S) with an elevation difference of 1100 m causes weak but steady katabatic winds (downslope buoyancy-driven flow) between the colder plateau and the warmer basin interior with a surface air temperature difference of 0.6 K. For mass continuity reasons, such katabatic winds in turn induce a regional-scale thermally direct meridional circulation such as that known from Antarctica (Parish & Bromwich 1991).

This local circulation extends from the slope up to the lower stratosphere, where the static stability is extremely high. Such circulation affects the ethane condensation for two different reasons: First, it causes significant adiabatic cooling and warming in the lower stratosphere (Figure 7(b)). The strong upwelling near 60°S locally suppresses the temperature at the ethane condensation level by 0.1–0.2 K relative to the zonal-mean temperature and thereby increases the ethane relative humidity (Figure 7(c)). The banded precipitation pattern at 60°–50°S can thus be explained by locally enhanced adiabatic cooling, which increases the relative humidity owing to decreased saturation vapor pressure. Second, topography locally increases the ethane abundance in areas of strong downwelling. This is the case at 30°–20°S along this longitude, where the area of ethane supersaturation is pushed downward relative to that poleward of 50°S. This mechanism also locally increases the ethane precipitation rate, yet this effect is weaker than the effect of increasing the relative humidity by adiabatic cooling. Third, the multiple-cell meridional circulation caused by topography causes some homogenization of the latitudinal ethane distribution in the lower stratosphere because the side-by-side presence of upward and downward ethane transport weakens the buildup of a strong meridional gradient in ethane abundance as is observed and predicted in the upper stratosphere. Therefore, the ethane accumulation at the winter pole in this altitude region is less pronounced than in the simulation without topography. Therefore, ethane precipitation right at the

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Figure 6. Same as Figure 5, but for the simulation with globally uniform geography (no topography).
winter pole is weaker than in the simulation without topography. The persistent ethane precipitation near 50°N is also caused by adiabatic cooling associated with the circulation over the large basin near 80°W.

Figure 8(a) depicts the global distribution of annual ethane precipitation in the simulation with baseline topography. The annual ethane precipitation tends to increase from equator to pole, but otherwise the geographic distribution is highly patchy. The largest annual precipitation (≈0.8 mm per Saturn year) is found inside Hagal Planitia Basin near 50°S/340°W and in a large topographic depression at ≈45°N/≈80°W. These maxima can be explained by localized strong adiabatic cooling over basins discussed above. Further ethane precipitation peaks (≈0.4 mm per Saturn year) exist near 45°N/315°W and 75°N/315°W (Kraken Mare). On the other hand, wide portions of flat areas at low and midlatitudes have annual precipitation of less than 0.01 mm per Saturn year, i.e., two orders of magnitude smaller than the global precipitation and its size are somewhat sensitive to topographic errors, yet the total ethane precipitation is not shown to be sensitive. However, the difference between the baseline simulation and simulation with minimum topography is much smaller than the difference to the simulation without topography. Changing the upper boundary condition for the ethane abundance has a larger impact on the ethane precipitation amount. Modifying the ethane mole fraction at the upper boundary after Equation (2) reduces the stratospheric ethane abundance and downward ethane flux by approximately

3.2. Sensitivity Study

This part of the study investigates to what extent the uncertainty of various boundary conditions affects the amount and geographic distribution of ethane precipitation.

As described in Section 2, Titan’s topography map is subject to large errors in some regions. Running the same simulation with the minimum topography map (Figure 1(b)) causes some changes in the global distribution of ethane precipitation. While the seasonal pattern and global annual amount of ethane precipitation change little, the geographic distribution changes to some extent (Figure 10(b)). The largest change is found in Hagal Planitia Basin (50°S/340°W), where the area of intense ethane precipitation becomes longitudinally stretched (Figure 8(b)). The ethane precipitation in the northern hemisphere becomes slightly more latitudinally uniform.

This example illustrates that the area of maximum ethane precipitation and its size are somewhat sensitive to topographic errors, yet the total ethane precipitation is not shown to be sensitive. However, the difference between the baseline simulation and simulation with minimum topography is much smaller than the difference to the simulation without topography.

Changing the upper boundary condition for the ethane abundance has a larger impact on the ethane precipitation amount. Modifying the ethane mole fraction at the upper boundary after Equation (2) reduces the stratospheric ethane abundance and downward ethane flux by approximately.
one-third. Condensation occurs essentially in the same area, altitude region, and seasons as in the baseline simulation since the temperature at the condensation levels does not change (Figure 10(c)). Also, the global pattern of annual ethane precipitation does not change (Figure 8(c)). However, since the ethane supply from the upper stratosphere is slower, the interval between consecutive condensation events at a given site is longer. This results globally in smaller precipitation rates (Figures 9(a) and 10(d)). The global annual precipitation reduces by 31% to 0.81 × 10^{12} kg per Saturn year. Despite this reduction, the global precipitation rate of 874 kg s^{-1} is still 36–175 times larger than the photochemical production rate (5–24 kg s^{-1}). An even smaller ethane abundance in the upper stratosphere (≤10^{-5}) corresponding to a smaller ethane supply from the mesosphere would no longer be consistent with the observed ethane abundance (e.g., Vinatier et al. 2015, 2020). The remaining realistic possibility to explain the difference between the global production rate and precipitation rate is an excessive meridional circulation in the GCM. This aspect, however, is beyond the scope of the current study.

3.3. Observational Constraints

The predicted ethane cycle of the present epoch can partly be compared to the spatial and seasonal variation in C\textsubscript{2}H\textsubscript{6} mole fraction, C\textsubscript{2}H\textsubscript{6} clouds, and temperature observed by Cassini in selected areas of the lower stratosphere in selected seasons. The minimum altitude at which the C\textsubscript{2}H\textsubscript{6} abundance could be retrieved from Cassini CIRS is 88 km. The observed C\textsubscript{2}H\textsubscript{6} at this altitude amounts to (1.0 ± 0.4) × 10^{-5} in northern winter and spring (years 2007–2017; Lombardo et al. 2019). The model prediction at this altitude (Figures 2(a)–(b)) is consistent with this observation. The Gas Chromatograph Mass Spectrometer (GCMS) on board the Huygens probe detected traces of

Figure 8. Global maps of annual ethane precipitation in the present epoch predicted in three simulations.
C$_2$H$_6$ in the lower stratosphere and troposphere near the detection threshold but could not quantify the C$_2$H$_6$ mole fraction (Niemann et al. 2010). The vertical-latitudinal distribution of ethane mole fraction (Figure 2) can be compared to that observed by Cassini CIRS from northern winter to summer (Figure 5 of Vinatier et al. 2015; Figure A.1 of Vinatier et al. 2020). The model reproduces the observed downward extension of ethane accumulation near the north pole in northern spring, as well as the steep decrease of ethane mole fraction in the lower stratosphere at all latitudes and in all seasons. On the other hand, the predicted ethane distribution in the southern hemisphere in northern spring is much smoother than observed. Especially, the observed intrusion of ethane-rich air from above near the south pole in late southern fall is not predicted (Figures 2(c)–(d)).

The predicted seasonal and geographic variation in ethane precipitation (Figures 6(d) and 7(d)) can be directly compared to the clouds monitored by the Cassini Visual and Infrared Mapping Spectrometer (VIMS; Rodriguez et al. 2009; Le Mouélic et al. 2018; Turtle et al. 2018). Clouds referred to as “VIMS tropospheric clouds” (Turtle et al. 2018) can comprise convective and stratiform methane clouds and ethane clouds in the lower stratosphere or upper troposphere but do not contain high-altitude (∼300 km) HCN clouds. Therefore, detection of clouds by VIMS in areas/seasons where no ethane condensation is predicted does not necessarily falsify the prediction as long as methane clouds are predicted instead. Moreover, some ethane clouds in the polar night may have been undetectable by VIMS. On the other hand, prediction of ethane clouds at lower latitudes and in seasons where no clouds at all were observed by VIMS would point to a misprediction by the model.

In the northern hemisphere clouds were observed in the polar region in early spring at various latitudes poleward of 30°N and, after some break, frequently around the northern summer solstice ($L_S = 90°$) at high northern latitudes. These early-spring clouds are predicted by the GCM with and without topography. However, the GCM with topography qualitatively better captures the observations in that the precipitation is predicted at different latitudes, while the precipitation in the nontopography GCM monotonically increases toward the north pole. The ethane precipitation in either GCM version largely disappears by late spring, when clouds were frequently observed. Since these clouds are likely to be methane clouds (Turtle et al. 2018; Tokano 2019), they do not falsify the predictions concerning ethane precipitation. Observational evidence of ethane clouds was found at 51°–68°N in northern winter (indicated by the box in Figures 6(d), 7(d), 10(b), and 10(d); Griffith et al. 2006). Strong ethane precipitation is predicted by the GCM with topography in this season, yet it appears at lower latitude than observed. The GCM with minimum topography (Figure 10(b)) and GCM without topography (Figure 7(d)) achieve a slightly better agreement. Likewise, the observed north polar clouds shortly before the vernal equinox are better reproduced by the GCM with minimum topography or without topography than that with baseline topography.

In the southern hemisphere the numerous clouds observed from late summer ($L_S = 300°$) to early fall ($L_S = 20°$) are likely to be convective methane clouds, so that they can be disregarded in this study. Later in southern fall, clouds were observed between 50°S and 70°S. They are reproduced by the GCM with topography, although it may be $∼10^7$ shifted to the north, while the GCM without topography predicts ethane precipitation only very close to the south pole, i.e., it is less consistent with the observation.

In summary, the baseline GCM generally reproduces the seasonal trend of observed putative ethane clouds and the latitudinal distribution of clouds in the southern hemisphere, but the predicted latitudinal distribution of clouds at high northern latitudes disagrees with the observation. The GCM without topography better reproduces the cloud characteristics near the north pole, while the prediction in the southern hemisphere poorly agrees with the observations. The discrepancy between the prediction by the baseline GCM and cloud observations in the northern hemisphere may point to a significant qualitative error of the topography in parts of the northern hemisphere as already noted in Section 3.2.

Spectroscopic evidence of liquid ethane possibly brought to the surface by rainfall was found in Yalalag Terra (17°S/325°W) at $L_S = 0°$ and $L_S = 8°$ and in Hetpet Regio (24°S/291°W) at $L_S = 11°$ and $L_S = 29°$ (Dalba et al. 2012). Although weak ethane precipitation is predicted in this season at low southern latitudes (Figure 6(d)), these areas generally belong to those with the least ethane precipitation rate (Figure 8). However, it is likely that the observed liquid ethane on the surface of these areas did not originate from stand-alone ethane precipitation, as predicted by this model, but was contained in the (methane) rainstorms. The predicted ethane precipitation of the order of $10^{-9}$ mm day$^{-1}$ might be too little to be identified by spectroscopy. This leads to the suggestion that the geographic distribution and amount of ethane precipitation in the equatorial region may highly depend on rare methane storms if the raindrops contain much ethane. At higher latitudes, where the predicted intrinsic ethane precipitation rate is higher, the climatology of ethane precipitation may be less dependent on methane storms.

Titan’s upper stratospheric temperature measured by Cassini CIRS exhibits evidence of eccentricity-driven cooling during
the Cassini mission (Bézard et al. 2018; Sylvestre et al. 2020) that is qualitatively similar to that predicted in the lower stratosphere by this GCM (Figure 6(a)). The altitude range below 70 km is not accessible to CIRS (Sylvestre et al. 2020), though. On the other hand, the temperature in the altitude range of ethane condensation (50–60 km) was sounded by Cassini radio occultations (Schinder et al. 2011, 2012, 2020) and CO submillimeter emission-line measurements by ALMA (Atacama Large Millimeter/Submillimeter Array; Thelen et al. 2018) at selected sites and times. In either hemisphere the observed temperature (57 km) at high latitudes is systematically higher than at low latitudes by 3–4 K (Figure 11(a)). The predicted temperature instead exhibits a slight temperature decrease with increasing latitude. The observed counterintuitive temperature increase with increasing latitude is unique to the altitude range between 55 and 70 km (Figure 3 of Schinder et al. 2012). Such a temperature profile cannot be explained by radiative effects given that the subsolar latitude around the equinox is near the equator. This effect may instead be a result of strong adiabatic heating at the poles in this season owing to downward wind at either pole, which is stronger than predicted by the GCM. Thus, the downward ethane transport at the poles in this season may be stronger than predicted by this model. This, however, may not lead to stronger ethane precipitation because of the warm polar temperatures. Aside from the equator-to-pole temperature contrast, the available

![Figure 10. Season-latitude section C2H6 mole fraction at 57 km altitude and C2H6 precipitation rate in the present epoch in simulations with the minimum topography map and reduced ethane flux at the upper boundary.](image)

![Figure 11. Temperature data at 57 km altitude at different points in the northern and southern hemisphere in different seasons retrieved by the Cassini Radio Science Subsystem (RSS; Schinder et al. 2011, 2012, 2020) are compared to the temperature at the same level predicted by the GCM. The radio occultation data at 57 km are obtained by linear interpolation of the data at 55 and 60 km altitude tabulated in the cited publications. The data are binned into low and high latitudes of each hemisphere.](image)
temperature data do not basically rule out the general trend and magnitude of the seasonal temperature variation predicted by the GCM. Hence, the predominance of eccentricity-driven temperature variations in this altitude range cannot be dismissed.

4. Evolution of the Ethane Cycle over the Past 100 kyr

Over the past 100 kyr Saturn has performed a little over two cycles of precession with a period of \( \sim 45 \) kyr (Figure 1 of Lora et al. 2014). Saturn’s eccentricity and obliquity underwent periodic oscillations on similar timescales. Perihelion at northern vernal equinox (\( L_S = 0^\circ \)) occurred at 34.7 kyr BP and 79.7 kyr BP, maximum eccentricity (\( \sim 0.08 \)) at \( \sim 13 \) kyr BP and \( \sim 68 \) kyr BP, minimum eccentricity (\( \sim 0.015 \)) at \( \sim 41 \) kyr BP and \( \sim 95 \) kyr BP, maximum obliquity (28\(^\circ\).3) at \( \sim 32 \) kyr BP and \( \sim 82 \) kyr BP, and minimum obliquity (26\(^\circ\).4) at \( \sim 7 \) kyr BP and \( \sim 58 \) kyr BP.

These orbital parameter variations directly affect the amplitude and timing of seasonal temperature variations in the entire atmosphere. Figures 12(a)–(b) show how the seasonal and latitudinal pattern of polar temperature at 57 km altitude, which is particularly relevant for ethane condensation, changed over the past 100 kyr. The most eye-catching pattern is the gradual shift of
the season of annual minimum and maximum temperature as one moves from 100 kyr BP to the present. In all epochs the lowest temperature occurs approximately one season past aphelion. This can be contrasted to the upper stratospheric temperature, whose seasonal variation mainly stems from the variation in solar zenith angle rather than that of heliocentric distance (Teanby et al. 2019). The annual temperature range is largest in epochs of high eccentricity, i.e., between 75 and 65 kyr BP and between 20 and 10 kyr BP.

In all epochs and in either hemisphere ethane precipitation primarily occurs in local fall and winter, i.e., at $L_s = 0°$–$180°$ in the south and at $L_s = 180°$–$360°$ in the north (Figure 12(c)–(d)). This is because orbital forcing does not substantially shift the seasonal timing of the reversal of the meridional-vertical circulation relevant for the ethane transport. However, a closer look at the time-latitude section of annual ethane precipitation reveals that the seasonal pattern varies with a period of ∼45 kyr (precession period). The largest ethane precipitation rate is found in epochs in which aphelion occurs in local fall or winter because the timing of seasonal cooling and downward ethane transport coincide. By contrast, ethane precipitation in a given hemisphere is particularly weak in epochs in which aphelion occurs in local spring or summer because warming acts to increase the saturation vapor pressure while ethane is being transported toward the cold trap.

The hemispheric asymmetry in annual ethane precipitation (Figure 9(b)) periodically reverses with the period of the Croll–Milankovitch cycle. The southern hemispheric ethane precipitation is larger than the northern counterpart during the past 15 kyr, between 30 and 50 kyr BP and between 78 and 100 kyr BP. The maximum hemispheric difference of the annual ethane precipitation amounts to 1.5 × 10$^{11}$ kg, or 25%. Ethane precipitation maximizes in that hemisphere, which experiences aphelion in fall or winter when downward ethane transport takes place. The globally integrated ethane precipitation per Saturn year amounts to 1.13–1.24 × 10$^{12}$ kg, corresponding to a liquid layer of 0.0208–0.0226 mm depth if distributed evenly on a spherical globe.

Despite the clear periodicity of ethane precipitation forced by the Croll–Milankovitch cycle, the latitudinal profile of annual ethane precipitation exhibits selected peaks off the poles in all epochs (Figure 12(e)). The largest peak in the northern hemisphere is always found near 50°N, while the southern hemisphere contains two local peaks (larger peak near 45°S and smaller peak near 75°S). The present epoch is characterized by intermediate ethane precipitation rates.

Integrating the annual precipitation rate over the past 100 kyr yields a cumulative ethane precipitation, which varies between 0.01 m near the equator and 0.27 m at 50°S and 45°N. The global average amounts to 0.0725 m over this period. Simple extrapolation to Titan’s age (4.5 Gyr) would yield a cumulative ethane precipitation of 3263 m, which would even exceed the initial estimate of 900 m based on pre-Cassini photochemistry (Lunine et al. 1983). This calculation assumes that the ethane abundance in the upper stratosphere and atmospheric structure have not changed over the past 4.5 Gyr, which is unlikely.

A more important finding of this study is that the cumulative ethane precipitation over the past 100 kyr exhibits a non-monotonic latitudinal profile and that ethane precipitation is not confined to the polar region.

5. Discussions

5.1. Lake Composition

Cassini RADAR observations revealed that Titan’s seas and lakes have different chemical compositions. Assuming a ternary mixture of CH$_4$, C$_2$H$_6$, and N$_2$, the volumetric C$_2$H$_6$ content in Titan’s seas/lakes constrained by Cassini RADAR amounts to 12$\pm$10% in Ligeia Mare (Mastrogiuseppe et al. 2018b), 0$^{+0}_{-8}$% in Punga Mare including Baffin Sinus (Mastrogiuseppe et al. 2018b), 15$^{+5}_{-3}$% in Winnipeg Lacus (Mastrogiuseppe et al. 2019), and 38$^{+36}_{-36}$% in Ontario Lacus (Mastrogiuseppe et al. 2018b). The composition of Kraken Mare could not be determined since the sea was either too deep or too absorptive for Cassini RADAR (Mastrogiuseppe 2019). These observations may point to some latitudinal variation and hemispheric asymmetry in the lake composition, in addition to that of the lake abundance.

Latitudinal variation in lake composition was expected already before observational data became available, although the predictions strongly differed from each other. Under the premise that the hydrocarbon mixtures in the lakes are in thermodynamic equilibrium with their atmospheric phases and the lake temperature monotonically decreases from equator to pole, the ethane content would slightly decrease from 80% at the equator to 76% at the poles (Cordier et al. 2009). Calculations with a simple hydrological model indicate that Ligeia Mare located at higher latitudes would contain less ethane than Kraken Mare provided the methane precipitation increases with latitude (Lorenz 2014). Another thermodynamic calculation yields that the ethane content in the seas would decrease from 42% in the southern basin of Kraken Mare to 29% in Punga Mare near the north pole (Tan et al. 2015). Once Ligeia Mare was found to be methane-rich, strong accumulation of methane near the north pole in the present epoch within the Croll–Milankovitch cycle, percolation of ethane, or transport of ethane from Ligeia Mare to Kraken Mare was suggested as a possible reason for the low ethane content of Ligeia Mare (Mitchell et al. 2015).

The area of maximum ethane precipitation around 60°S is located within Hagal Planitia Basin, which is well separated from the catchment area of Ontario Lacus according to Dhingra et al. (2018). Thus, the ethane precipitation here probably does not drain to Ontario Lacus. On the other hand, the catchment area of Ontario Lacus, approximately bounded by the 95°W and 210°W meridians and 40°–50°S latitude, receives a predicted annual ethane precipitation of 0–0.2 mm per Saturn year depending on geographic location (Figure 8). Part of this ethane precipitation should be responsible for the observed ethane content of Ontario Lacus. The putative catchment areas of the northern seas are approximately bounded by the 210°W and 350°W meridians and 55°N latitude (Lorenz 2014). The predicted annual ethane precipitation in this catchment area also varies between 0 and 0.2 mm per Saturn year. Therefore, the predicted geographic distribution of ethane precipitation by itself cannot explain the observed difference in the ethane content between Ontario Lacus and the northern seas and probably reflects the hemispheric asymmetry in methane precipitation (Lora et al. 2014; Tokano 2019).

A natural question that arises in this context is whether the predicted periodic reversal of the hemispheric asymmetry in the hemispheric ethane precipitation is capable of periodically reversing the hemispheric asymmetry in lake composition. The
predicted time series of hemispheric ethane precipitation (Figure 9(b)) implies that one hemisphere receives up to \(2 \times 10^{13}\) kg, or 30 km\(^3\) more ethane precipitation than the opposite hemisphere over a period of \(\sim 20\) kyr. If all ethane precipitation in the southern hemisphere drains to Ontario Lacus, whose volume varies between 250 and 500 km\(^3\) owing to secular variation in methane precipitation (Tokano 2021), the predicted variation in ethane precipitation would change the ethane content at most by 10% over the course of the Croll–Milankovitch cycle. In reality, the catchment area of Ontario Lacus covers 11% of the southern hemisphere (Dhingra et al. 2018), which would reduce the ethane input to Ontario Lacus by one order of magnitude and reduce the secular variation in ethane content of this lake to 1%. It is therefore likely that Ontario Lacus is permanently more ethane-enriched than the northern seas. Apart from this, the influence of variable ethane precipitation on lake size variation should be negligible for all seas and lakes.

5.2. Implication for the Shape of Titan

Choukroun & Sotin (2012) proposed that ethane precipitation near the poles percolates to the clathrate hydrates and substitutes the methane molecules. This would cause an isostatic subsidence of the polar crust, i.e., polar flattening in excess of the flattening caused by Titan’s rotation. This idea was tacitly based on the assumption that ethane precipitation peaks at the poles as predicted by Rannou et al. (2006) and Griffith et al. (2006). According to Figure 2 of Choukroun & Sotin (2012), the subsidence of the crust scales with the total mass of precipitated ethane and depends on the porosity of the crust and equatorward latitudinal extent of ethane precipitation.

The predicted nonmonotonic latitudinal and longitudinal variation in cumulative ethane precipitation implies that the subsidence of the crust by this effect may not simply increase from equator to pole but may vary geographically in a more complex fashion. As already discussed in Section 3.1, areas of enhanced ethane precipitation generally coincide with the locations of large or deep basins. Therefore, ethane precipitation may magnify the crustal depression by this mechanism in those regions that are already topographically depressed. Where ethane precipitates on polar seas, ethane percolation would occur at the seabed (Figure 3 of Choukroun & Sotin 2012), but in large seas it may be mixed horizontally (Tokano & Lorenz 2016) before percolation. In other words, ethane percolation would maximize in the deepest portions of the seas, which may be located off the north pole. This also applies to paleoceans, which may have existed in the southern hemisphere in the past (Birch et al. 2018). As a whole, ethane precipitation may act to increase the irregular shape of Titan. However, were Titan’s shape always concentric about the poles, ethane precipitation would be concentric about the poles as well, so it would not cause a nonconcentric crustal depression. Therefore, additional causes beyond the scope of this study would be required to explain Titan’s irregular shape.

Finally, recent laboratory experiments show that reactions of liquid ethane and methane with ice can produce clathrates on seasonal timescales (Vu et al. 2020). This illustrates the importance of the climatology of both methane and ethane precipitation on Titan in the consideration of clathrate formation and evolution.

6. Conclusions

Previous work assumed or predicted that ethane precipitation on Titan is confined to the polar region, with possible implications for Titan’s polar flattening (Choukroun & Sotin 2012). Cassini, however, showed that the northernmost sea (Punga Mare) is poorer in ethane (Mastrogiuseppe et al. 2018b) than Ontario Lacus at high southern latitudes (Mastrogiuseppe et al. 2018a). Motivated by these observations and theoretical models, this study investigated which factors determine the latitudinal distribution of ethane precipitation and how this may have changed in the recent past.

A Titan GCM was used to predict the geographical, seasonal, and long-term pattern of ethane condensation in a series of paleoclimate simulations. If Titan’s globe were flat and uniform, the annual ethane precipitation would monotonically increase with latitude as was already predicted by a previous model (Rannou et al. 2006). If the geography observed by Cassini is taken into account, the geographic distribution of ethane precipitation becomes more patchy. Most ethane precipitation then occurs over large basins at mid-latitudes rather than right over the poles. Local enhancement of ethane precipitation over basins is caused by a circulation associated with katabatic winds, which causes strong adiabatic cooling in the lower stratosphere in regions of upwelling. Secondary maxima of ethane precipitation occur within the same circulation in areas with strong downward ethane transport.

Orbital parameter variations affect the annual temperature range and the seasonal timing of temperature maximum and minimum. Ethane precipitation seasonally intensifies when aphelion occurs in local fall or winter. The annual ethane precipitation, however, changes by at most 25% owing to orbital forcing.

The sea/lake composition is not likely to substantially change owing to orbitally forced secular variation in ethane precipitation. Possible changes in lake composition are more likely to be caused by long-term variation in methane precipitation. On the other hand, the geographic variation in ethane precipitation may have some influence on Titan’s shape. Since the geographic distribution of ethane precipitation is not concentric about the poles but maximized in large basins at midlatitudes, percolation of ethane precipitation would preferentially occur where the crust is already depressed. In combination with the mechanism of ethane-methane substitution in clathrate hydrates proposed by Choukroun & Sotin (2012), this would act to increase Titan’s topographic variations by further deepening the basins.

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ORCID iDs

Tetsuya Tokano @ https://orcid.org/0000-0002-7518-9245

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