Understanding the influence of topography on Titan's asymmetric lake distribution

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CONTENTS

ABSTRACT

Titan is the only planetary body in the Solar System, other than Earth, known to have an active hydrologic cycle. On Titan, Saturn’s largest moon, methane and ethane rain out of the atmosphere to feed lakes and seas. Due to its vigorous hydrologic cycle and its chemical similarities to prebiotic Earth, Titan is an important analogue to our planet. Over the last decade, the Cassini-Huygens flybys uncovered a stark asymmetry in the distribution of lakes and seas on Titan’s north and south poles. Proposed causes range from seasonal and orbital to topographic influences. Tokano (2019) concludes that hemispheric differences in topography determine Titan’s seasonal climate asymmetry on a semi-permanent scale, which resists the 45kyr Croll–Milankovitch cycle. In contrast, we test the spatial and seasonal influence of surface features on Titan's hydrologic cycle using a higher-fidelity general circulation model (GCM) to evaluate those claims. We compare two topographical simulations: one where the observed topography governs only the GCM’s surface hydrology, and another where the topography also interacts directly with the GCM’s atmosphere to produce climate patterns. Contrary to Tokano (2019) we show that coupling of topography with the atmosphere is not solely responsible for asymmetric climate patterns and surface methane distribution. In both our simulations, the climate system efficiently transports methane to northern regions. We find that Titan’s topography interacts with the lower atmosphere to cause polar increases in seasonal heating relative to the control simulation. This leads to warmer northern summers and significantly warmer and shorter southern summers. At both poles, net evaporation increases and surface methane buildup is reduced. We also observe the potential formation of a new northern lake and the disappearance of previous southern lakes. In a third simulation, we also include surface roughness in the model, which results in the net wetting of northeastern and southern regions. In summary, our findings have broad implications: surface features are vital in the design of high-accuracy Titan GCMs. While unlikely to produce Titan’s vast asymmetry in polar deposits in isolation, surface features create a non-neglible impact on the atmosphere and should be factored into the design of future Titan GCMs.

INTRODUCTION & GUIDING QUESTIONS

BACKGROUND ON TITAN

Titan is the only planetary body in the Solar System, other than Earth, known to have an active hydrologic cycle, operating on timescales of days to thousands of years (Hörst 2017). On Titan, Saturn's largest moon, methane and ethane condense out of the nitrogen-based atmosphere and flow as liquids over the surface, forming stable bodies of liquid, some as much as hundreds of meters deep (Hayes, Lorenz, and Lunine 2018; Birch et al. 2018; Mastrogiuseppe et al. 2019). A few of these bodies of liquid are even comparable to some of the deepest and largest lakes on Earth[1]: Titan's northern Kraken Mare is huge, and "almost as large as all five of the Great Lakes in North America, combined" (Poggiali et al. 2020). Similar to the Earth's hydrologic cycle, which has guided the evolution of life and the transport of nutrients, materials, and sediment across our planet, Titan's vigorous hydrologic cycle includes atmospheric, surface, and subsurface components, all of which play essential roles in Titan's climate system and distribution of liquids (Horvath et al. 2016; Faulk et al. 2020). Methane and ethane rain out of Titan's atmosphere and etch channels as they flow across the moon's icy surface. This feeds the lakes and seas, which then evaporate back into the atmosphere or drain into the subsurface, leaving reservoirs of liquid below the surface (Mitchell and Lora 2016; Mastrogiuseppe et al. 2019). Because of Titan's colder climate with surface temperatures of approximately 90-95K, methane and ethane[2] dominate Titan's liquid processes, while water remains locked up in the form of rock-hard ice.

Due to unique features such as these, Titan's climate system is a revolutionary finding and a topic of continual interest for astrobiologists today. Many researchers view Titan as a time capsule, giving us a glimpse of what conditions on Earth may have looked like before life emerged. Though Titan is colder than Earth and lacks breathable oxygen, it hosts an inventory of organic compounds thought to be similar to those on Earth before life took hold (Raulin et al. 2012; Iino, Sagawa, and Tsukagoshi 2020). It has been speculated that life could even exist in the liquid methane and ethane that form

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[1] Europe's and America's deepest lakes are Hornindalsvatnet in the Norway fjords, 514m, and Crater Lake in Oregon, 592m. As of now, current understanding is that some of Titan's lakes may be as much as 300-400m deep.
[2] On our much-warmer earth, these hydrocarbons appear as gases.

rivers and lakes on Titan's surface, just as organisms on Earth live in water[3] (C. P. McKay and Smith 2005; C. McKay 2016). To advance our search for extraterrestrial life, NASA's Dragonfly mission[4], slated to reach Titan in the 2030s, will be assessing this exotic moon's habitability and search for signs of past or potential extant life. These are among the reasons our team is interested in investigating Titan and building a high-fidelity model to simulate its complex climate system and its evolution.

HYDROLOGY & SURFACE LIQUIDS

During its 13-year exploration of Saturn's system from 2004-2017, the radar mapping instrumentation on the Cassini-Huygens orbiter revealed significant details about Titan's atmosphere and hydrology, including the features described above. It also uncovered a significant asymmetry in the distribution of seas and lakes between Titan's northern and southern regions (A. Hayes et al. 2008; A. G. Hayes 2016; Stofan et al. 2007). There are three times more empty lakes in the North than the South and seven times more partially filled ones (Aharonson et al. 2009; A. Hayes et al. 2009; Mastrogiuseppe et al. 2019). The cause of this stark asymmetry of surface liquids has been a mystery.

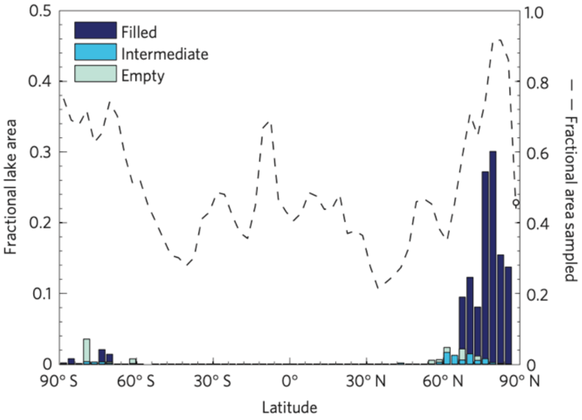

Figure 1. Lake latitudinal distribution. This image shows the vast hemispheric difference in the distribution of surface area between the northern and southern latitudes.

Source: Aharonson et al., 2009

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[3] Such hypothetical life would take in H_2 instead of O_2, react it with acetylene instead of glucose, and produce methane instead of CO2; in contrast, some of earth's methanogens acquire energy by reacting H2 with CO2, producing methane and water. (C. McKay 2016).

[4] Dragonfly's expected launch is in 2027.

Why the asymmetry?

The first question is whether the asymmetry in distribution of seas and lakes represents a persistent or seasonal/shorter-lived trend. From what we can glean from observations and models, the existence of the empty basins suggests a *longer*-term history and transport pattern that extends beyond the seasonal effects of methane evaporation and condensation over the course of one Titan year (one Titan year is 29.5 Earth years). The reservoirs have a depth that would not be able to fully drain or fill over a 15-year season (Aharonson et al. 2009). This is also supported by various climate models (Graves, Schneider, and Schaller 2009; Mitchell 2008). While Titan's localized surface liquids may fluctuate over the timescale of multiple years (Turtle 2009; A. Hayes et al. 2009), the levels of transport needed to create entire lakes over a purely seasonal timescale seems to be too far in excess of the peak evaporative energy flux available of ~2W m^{-2} (Mitchell 2008; Aharonson et al. 2009).

However, various other hypotheses exist that make a case for a more persistent hemispheric difference in Titan's surface liquids, maintained over *longer timescales*. Mechanisms involved include evolving orbital forcing, and the influence of topography over atmospheric circulation patterns. Our investigation centers on this part of the ongoing debate.

The "eccentricity" argument

Today, the leading hypothesis is that Saturn's orbital eccentricity[5] forces this longer-term, uneven distribution. After all, similar variations in Earth's orbit help drive our own paleoclimate cycles and are a critical parameter for accurately modeling the climate of our home planet[6]. Due to its eccentricity in its current orbital configuration, Titan is about 12 percent closer to the sun during its more intense and shorter southern

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[5] Eccentricity is the amount by which an orbit deviates from a perfect circle; presently, Saturn's is 0.055, Earth's 0.017.

[6] Eccentricity, obliquity (tilt in axis of rotation), and precession (change in the axis of rotation over time) make up Croll-Milankovitch cycles, which influence longer-term climate patterns. On Earth, our precession cycle of ~20k years and eccentricity of ~100k years contribute to ice ages.

summer. This intense southern summer[7] may lead to net evaporation (Aharonson et al. 2009), while the longer northern summer may experience higher precipitation (Schneider et al. 2012). The difference in seasonal evaporation and precipitation may explain a net transport of methane from south to north[8]. A number of publications have investigated these potential mechanisms; studies that reproduce or support this include Schneider et al. 2012; Lora, Lunine, Russell, and A. G. Hayes 2014; and Lora, Lunine, and Russell 2015.

Of relevance, in 2014, our lab's Titan general circulation model (GCM) was run using four configurations of orbital parameters[9] over the past 42 kyr to capture the effects of a range of cyclic variations in eccentricity. Each configuration was first spun up for twenty Titan years (~600 Earth years), then run for an additional 40 Titan years (~12,000 Earth years) per configuration, after which differences appear that are directly attributable to the different insolations. The results confirm the hypothesis that orbital forcing influences the asymmetry in lakes/seas. In the case reflecting present-day orbital configurations and the case reflecting the past 14 kyr (with maximum eccentricity), methane built up preferentially in the *north* (as observed), where the summer was mild and long. In the case for 42 kyr ago (minimum eccentricity), the south and north polar seasons were of similar intensity and duration, and the poles experienced latitudinally *symmetric* surface methane buildup. And in the case for 28 kyr ago (midpoint of the two), the south gained more methane.

The study reveals the role of orbital eccentricity in controlling today's northern preference of transport and suggests the hemispheric difference could have been partially or fully reversed in past cycles. (This could also help explain Cassini-Huygens's observation of empty basins in the south; other long-empty basins may have been obscured by surface processes since past configurations.) In this understanding, Titan's surface liquid reservoir is transported on ~30 kyr timescales due to orbital cycles, and following cyclic changes in eccentricity, asymmetry may fully reverse within ~125 kyr periods (Lora et al. 2014).

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[7] Southern summer solstice results in a 25% higher peak solar flux than northern summer. (Aharonson et al. 2009; Schneider et al. 2012)

[8] Similar variations in Earth's orbit help drive our own paleoclimate cycles.

[9] orbital eccentricity, obliquity, semi-major axis, and solar longitude of perihelion.

The “topography” argument

Yet other hypotheses exist that counter this. Most significantly, Tokano (2019) argues for the previously underestimated role of large-scale topography in modifying the circulation and uneven sea distribution. His work draws inspiration from Mars climate models, which have shown that Mars’s stark topographic differences between the hemispheres are enough to drive a seasonal asymmetry in meridional circulation, even if Mars’s orbit were perfectly circular and thus the insolation pattern were seasonally symmetric (Richardson and Wilson 2002).

Tokano argues that the accumulation of Titan’s lakes in the north could be a “semi-permanent feature” driven by topography on a scale that “resists the 45kyr Croll–Milankovitch cycle” (Tokano 2019). Like the Lora et al. (2014) simulation of varied orbital configurations, the study models Titan’s climate under orbital parameters of four different epochs, though using a different GCM from the University of Cologne, Köln (the “Köln GCM”). Tokano’s study runs each epoch’s case for nine Titan years total (~260 Earth years). Each simulation is conducted under two different geography patterns: (A) “globally uniform” topography and (B) “observed topography” exerting influence on atmosphere and climate.

The results are surprising. Under “uniform topography”, no combination of orbital parameters results in northern accumulation of surface methane (differing from observations and previous models). A colder and longer northern summer is found in every “observed topography” run compared to “uniform”, regardless of epoch (orbital forcing). All “uniform” runs see roughly symmetric amounts of annual precipitation in the north and south, with dry deserts in the equatorial tropics. Orbital forcing is found never to result in hemispheric asymmetry. Tokano concludes that hemispheric differences in topography determine Titan’s seasonal asymmetry in climate. Orbital parameters may minutely affect precipitation yet are unable to reverse or produce vast hemispheric asymmetry in polar deposits.

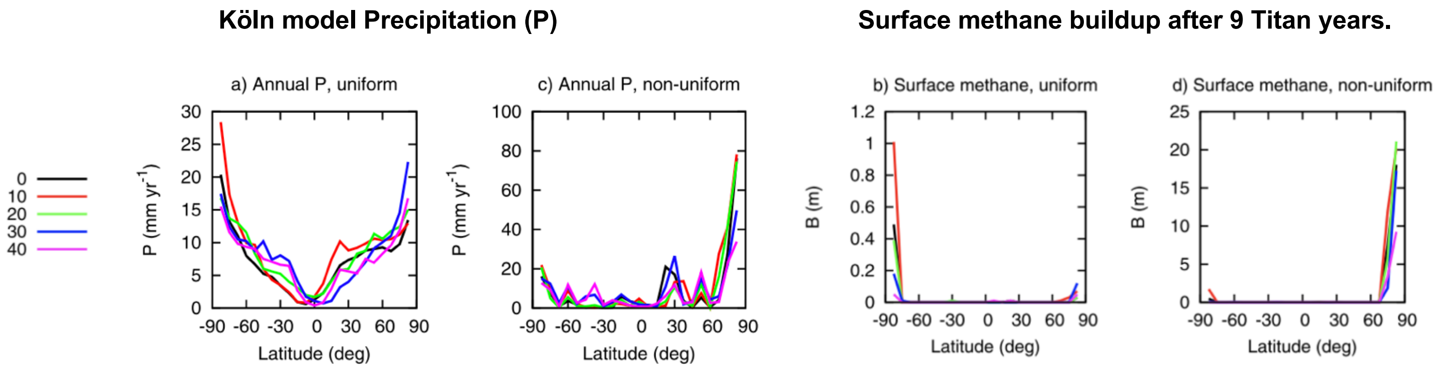

Figure 2. Topography is the only parameter creating the asymmetry in the Köln model. Colored lines represent different epochs of orbital forcing. As seen here (note the different scale bar on the left/“uniform” cases), there is very little P and barely any surface liquid accumulating in the uniform run. But above 82N, Tokano has increasing P and liquids for the “topography” run. Each line is a result after a 9-year run. Source: Tokano, 2019

The Tokano (2019) study complicates our picture of the importance of eccentricity to the climate. It suggests that topography is a critical input for modeling atmospheres and in some cases, can completely reverse hydrologic patterns. At the same time, how much of Tokano’s results are model-dependent? (For example, many Earth climate studies run ensembles of multiple GCMs in order to even out model-dependent biases and conclusions.) Is nine Titan years long enough to produce stabilized hydrology patterns and surface reservoirs? Additionally — as a thought experiment — if geographic topography is critical for *creating* surface liquids and asymmetries in hydrology, how did the anomalous geography originate (in a chicken-and-egg sort of way, must it have originated via non-hydrologic, e.g., volcanic, processes)?

Tokano’s results form a launching point for our study. Over the summer of 2020, our team developed a topographic and surface roughness dataset to be fed into our higher-fidelity GCM (Titan Atmospheric Model, “TAM”; Lora et al., 2015). Compared to the Köln GCM, our model better reproduces Titan’s meridional temperature gradients and zonal winds (Lora et al. 2019) and aspects of Titan’s surface hydrology (Faulk et al. 2020). In this project we integrate new surface features and allow them to interact with our model’s atmosphere, in order to evaluate their role and importance.

OBJECTIVES

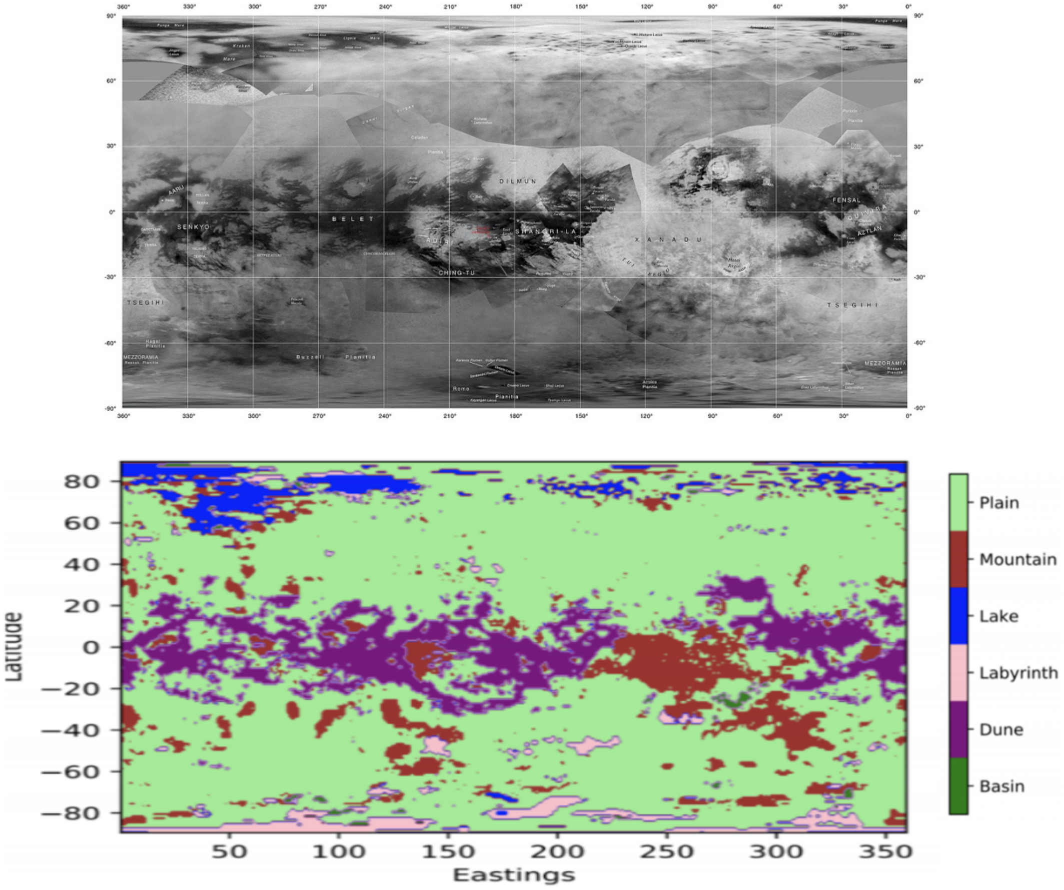

Figure 3. Labelled global maps of Titan with surface lakes/seas. Top: Titan's large bodies of surface liquids are known as *maria* (seas) and the small ones are known as *lacūs* (lakes). Kraken Mare, the largest sea on Titan, is at the top left. Ligeia Mare is to its east, and Punga Mare is to its west. (Source: NASA, Aug 2016).
Bottom: Categorized global map of Titan's surface features, drawing from updated topography map produced by Corlies et al. (2017).

There is clear evidence for Titan's active hydrological cycle. But significant work remains to understand the precise nature of Titan's hydrological cycle and the parameters that control it. As we seek life in the outer reaches of the Solar System, Titan is a crucial body to model due to its unique climate, astrobiological potential, and analogous features to Earth. With this challenge in mind, our study focuses on elucidating how Titan's surface parameters influence the atmospheric processes and hydrologic cycle in our Titan GCM.

To pinpoint the role of topography on the climate, we compare two simulations: one where observed topography only governs surface hydrology (the “control” case, equivalent to simulations in Faulk et al., 2020), and one where topography also interacts directly with the GCM’s atmosphere to alter circulation patterns (“topography” case). Our investigation aims to answer two guiding questions:

1. What is the influence of topography on the distribution in liquids?[10]
2. What is the difference between our findings and Tokano’s (2019)?

By answering these questions, we seek to better understand Titan’s climate and elucidate the importance of geography and topography to atmospheric and hydroclimatic behavior.

METHODS

Experimental Setup

To understand the role of topography on the climate, we first compare two simulations, described below. As background, Titan’s topography is extremely varied: for example, topography ranges from Titan’s peaks, such as Sotra Patera[11], down to several deep pits. The peaks are about 1,000-1,500m tall. The following equicylindrical maps visualize topographic inputs for the scenarios:

(A) **“Control” case** which does not have any topographic influence on the atmosphere.
(B**) “Topography” case** which experiences topographic influence on the atmosphere.

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[10] We seek this answer by comparing hydrology between the “control” and “topography” cases in the stabilized results of our model.

[11] A peak of Titan that is called by some “the very best evidence, by far, for volcanic topography anywhere documented on an icy satellite” (Jeffrey Kargel of the University of Arizona).

Topography for Surface Hydrology (both scenarios)

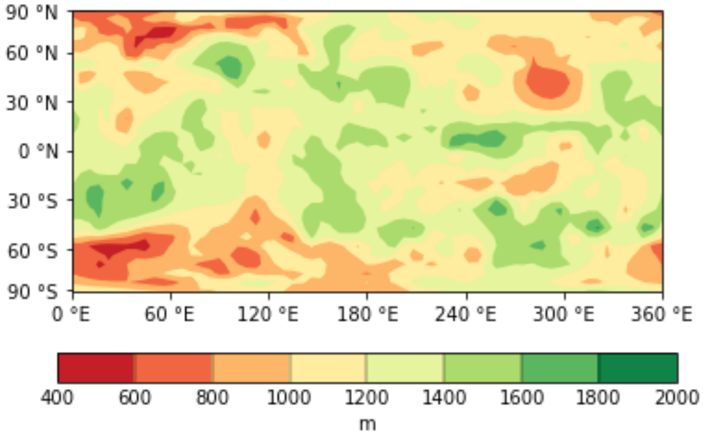
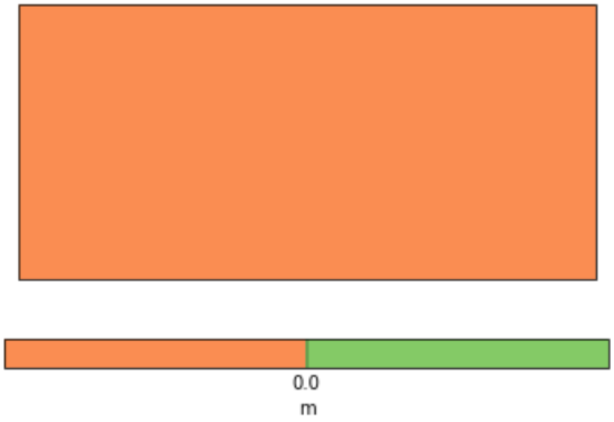


Figure 4. Map showing the topography that governs surface hydrology in BOTH cases (A and B). This surface hydrology configuration was tested and implemented in Faulk et al. (2020). This helps our GCM generate accurate surface hydrology that matches observations. The source of this topography comes from Corlies et al. (2017). Scale bar is global elevation (m) above the topographic minimum.

Topography used in Atmospheric Interactions

A) CONTROL



B) TOPOGRAPHY

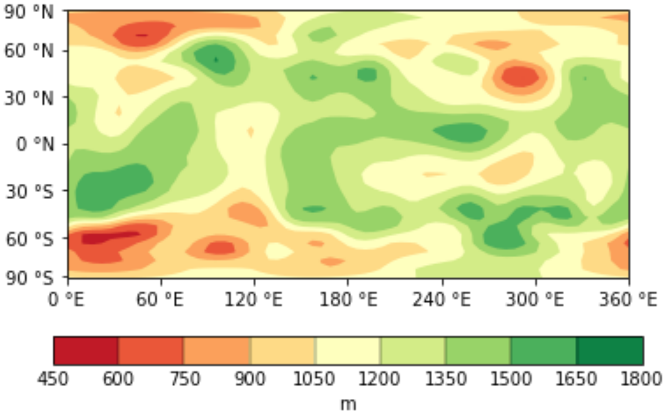


Figure 5. Unique topography that interacts with the atmosphere in each simulation.
(A) The control sees a globally uniform topography, with no coupling between the real surface height and atmospheric processes. (B) The test case inputs this dataset of smoothed topographic heights.[12] Anomalies in surface height influence the model's surface temperatures and atmospheric dynamics.

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[12] Categorized surface features (such as high mountains, or deep labyrinths) can be referenced in Fig. 3.

We also run a few additional iterations, including a “surface roughness” (SR) case which allows heterogeneous surface roughness to alter winds and thermal differences in the lower atmosphere:

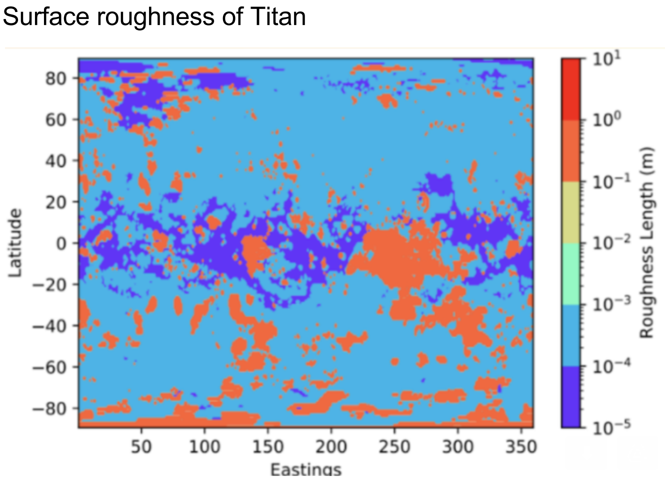

Figure 6. Surface roughness lengths corresponding to simulation case “SR”.

Finally, we run a cumulative “surface roughness + topography” case (TSR) which allows both the surface roughness (Fig. 6) effects and topography-influenced atmosphere (Fig. 5B) effects to interact. Iterations SR and TSR aim to further flesh out the role of surface features in producing seasonal climate trends and surface methane asymmetries.

All results reported in this thesis have been run for a simulation length of at least 150 Titan years[13] (~44,000 Earth years). At this point in the run, some ongoing fluctuations between the surface, subsurface and atmospheric methane reservoirs remain, meaning that the model has not fully stabilized yet[14]. However, we have confirmed that the large-scale precipitation, evaporation, and surface hydrology patterns we report on here seem to have largely stabilized. Where possible, 30-Titan-year decadal averages have been used in the analysis.

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[13] Some have been run out to 180 Titan years.

[14] Possibly due to the amount of conserved methane entered as an initial condition to the model.

Model Description: TAM

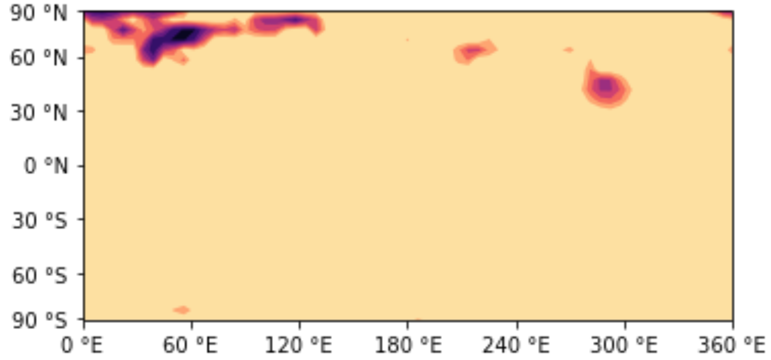
Our GCM (TAM) includes an atmospheric model with a methane cycle and surface reservoir, realistic land hydrology, and new (2020-2021) coupling between surface features and the atmospheric model. The atmospheric model is three-dimensional (3D), in contrast to previous two-dimensional (2D) models; observed intermittency of clouds and features such as equatorial super-rotation demonstrate the importance of 3D dynamics (Lora et al. 2019). TAM includes surface, subsurface, and atmospheric reservoirs of methane; the surface reservoir gains or loses methane according to local rates of precipitation and evaporation. Zonal and temporal averages can be generated and reach statistically steady states, which do not depend on initial conditions except for the total methane amount present in the atmosphere-surface system, which is conserved. TAM also includes a comprehensive and realistic surface hydrology scheme that includes parameterizations of overland surface liquid flow, infiltration, subsurface flow and ground-methane evaporation (Faulk et al. 2020). This fully coupled 3D atmosphere and land climate model allows methane to dynamically distribute itself within the climate system on various levels. The model reproduces the observed present-day temperature profile and tropospheric methane cycle (Lora et al. 2019). The atmosphere efficiently transports methane poleward, drying out low and mid-latitudes, matching observations. In low latitudes, rare but intense storms occur around the equinoxes, producing strong precipitation that may have carved out surface features in Titan's past and present.

The simulations for this thesis apply present-day orbital configurations. Surface topography (Fig. 3, Fig. 5B) and surface roughness (Fig. 6) coupled to the behavior of the lower atmosphere are added in the 2020-2021 simulations of our study. Below, the results section presents the results of our simulations and shows the relative role of topography-atmosphere interactions on the seasonal asymmetry in Titan's climate.

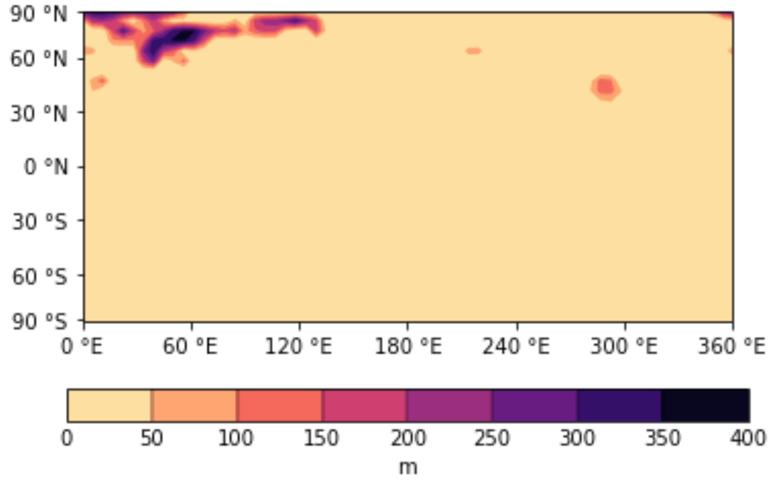
RESULTS & DISCUSSION

DISTRIBUTION OF SURFACE METHANE

(A) CONTROL



(B) TOPOGRAPHY



(C) Difference between simulations (Topography - Control)

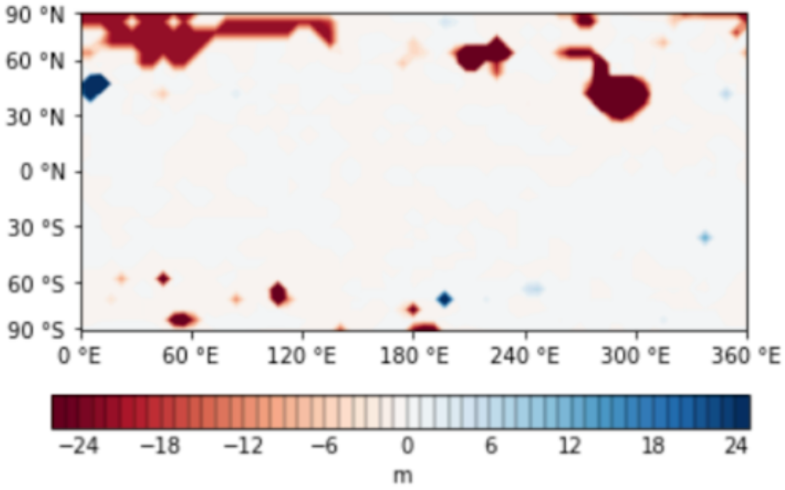


Figure 7. Surface Distribution of liquid methane by Titan year 150. In (A) and (B) the dark areas correspond to areas of greater depths of surface methane. The scale bar is the same for both.

(C) is difference between simulations, B – A. The darkest values in the map correspond to areas of >25m methane difference between simulations.

Comparison of our results with Cassini-Huygens's observed radar imagery

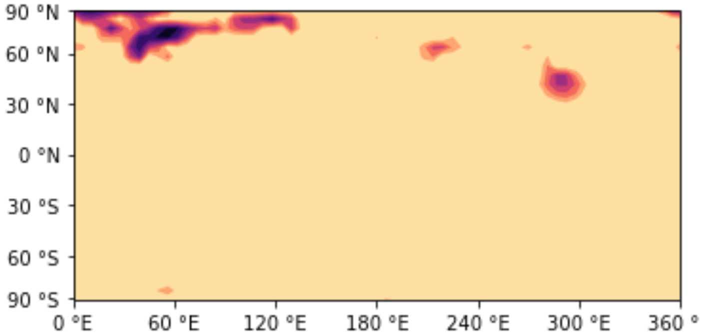


Figure 7A. Titan's surface liquid deposits as represented by our control simulation. The lakes match up to the size and shape of the seas visible in the radar imagery (dark basins in the northern hemisphere)

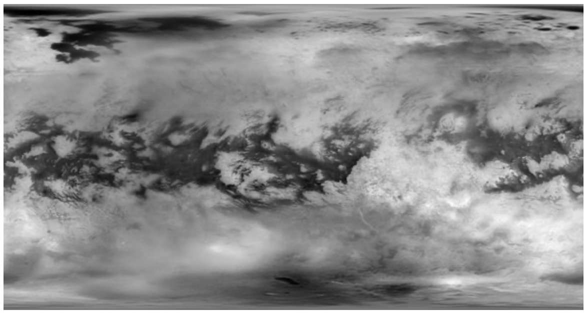


Figure 8. Titan's surface features (under the haze). Researchers have identified asymmetric polar methane deposits including three seas and 34 lakes, seven of which are dry. (NASA, Dec 2018)

Fig. 7 shows the distribution of surface methane from Titan years 141-150 of our run, alongside a comparative map that shows the difference between simulations. The data is significant for three reasons.

Northern preferential methane transport

First, the vast hemispheric asymmetry and preferential northern buildup of methane was visible in both the control and topo runs. This suggests that parameters of our GCM's control run, including present-day orbital parameters and surface topography coupled with the surface hydrologic transport, are sufficient to generate the observed pattern.

Matching Cassini-Huygens's observed surface features

Second, while Tokano's run with globally uniform topography and present-day orbital configurations failed to generate *any* significant surface liquids (Fig. 2) (let alone the observed northern preferential asymmetry) the methane surface patterns of TAM's Fig. 7A and 7B closely predict the radar-imaged distribution and shape of surface lakes and seas in as captured by the Cassini-Huygens flybys (Fig. 8). These attributes demonstrate the high fidelity of our GCM and suggest that fundamental issues may exist with Tokano's results (2019). Potential flaws leading to Tokano's inability to build perennial surface methane in any epoch of his control could include inadequate length of simulation timescale in order to achieve surface reservoir stabilization[15], and the Köln GCM's documented underestimation of meridional temperature gradients and inability to model accurate zonal winds, which would control moisture transport (Lora et al. 2019).

Reduction in polar liquids

Third, we find that both polar regions have less methane in our GCM's topography run (Fig. 7C). The dark red and dark blue regions of Fig. 7C represent >25m in surface liquid change, which is fairly significant. The southern region of the topography run has no significant southern lakes. The northern basins between 200-300°E, sitting in low-lying areas, experience a shrinkage of lake area and depth on the scale of 100m. In the high mountains of the south pole between 0°E and 180°E, deep basins of 50m which existed in the control run have completely disappeared (Fig. 7A-7B). This is akin to the disappearance of Seattle's entire Lake Washington.

Fourth, these results are the polar opposite of Tokano's results for surface liquids. Above 82°N, Tokano finds *increasing* surface liquids when topography is added to the model; in ours, we have decreasing surface liquids at that area. Our next set of analyses seek to elucidate drivers of these patterns.

High-level summary

Overall, the initial findings show that coupling realistic topography to the 3D atmospheric model can have an important, non-negligible impact on the overall weather patterns and hydrologic features. But while this may have a spatial and hydrologic effect, as seen in the smaller size of the lake at 50°N, 300°E, or the disappearance of southern basins, in isolation, it does not seem to be responsible for asymmetry like Tokano concludes. In the following sections we discuss in greater detail some of the mechanisms driving the patterns we observe.

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[15] Our own model's hydrologic patterns were far from stable at Titan year 9.

SEASONAL TEMPERATURES

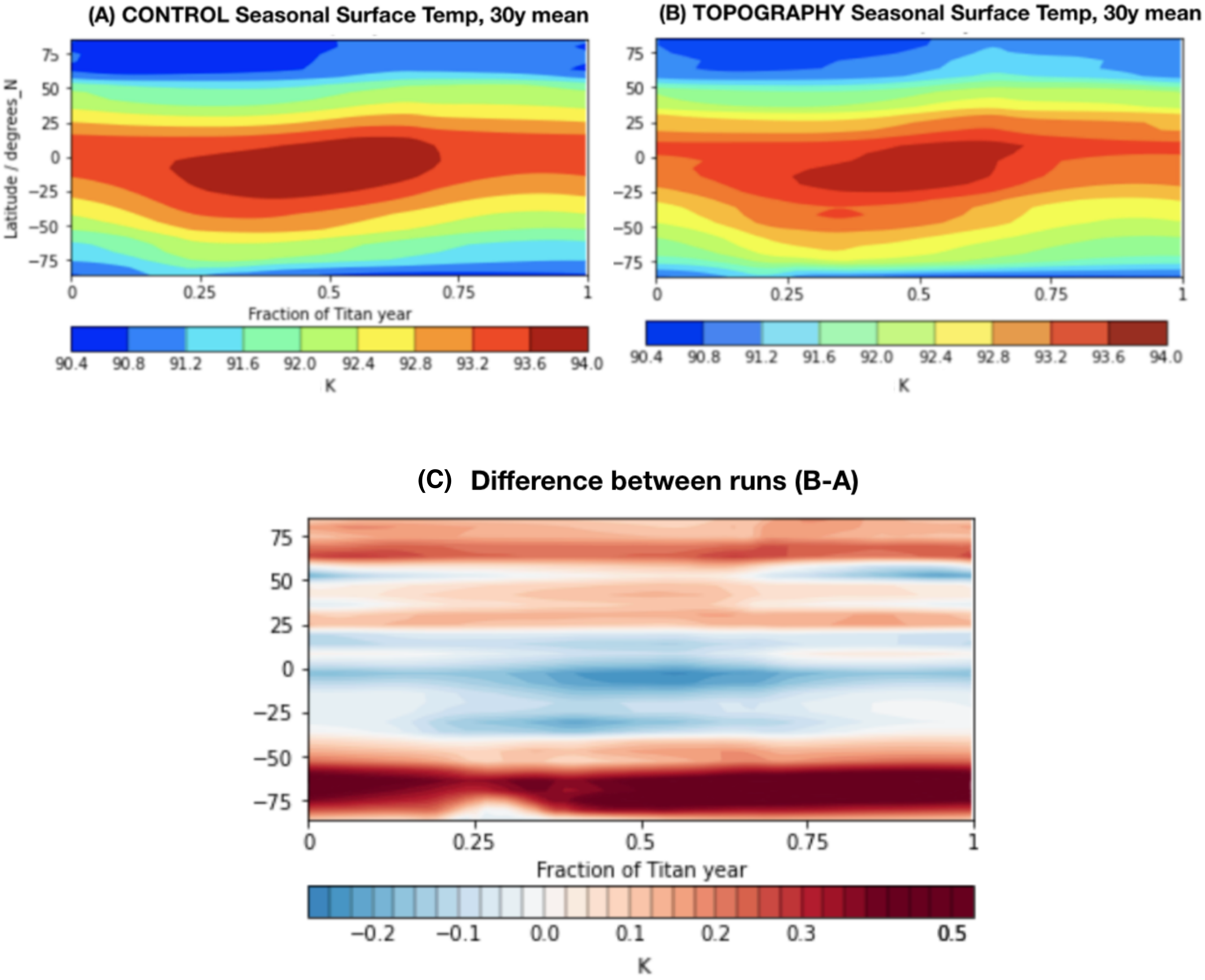


Figure 9. Latitudinal seasonal temperatures. Temperatures in Kelvin (K) are averaged over Titan years 121-150. Southern summer occurs around the 0.25 fraction of year (x-axis). Northern summer occurs around the 0.75 fraction.

How surface height impacts surface temperature

In its current orbital configuration, Titan's climate system features a shorter, stronger southern summer and a longer, more mild northern summer (Fig. 10a). This is thought to lead to the overall hemispheric asymmetry of surface deposits. We compare latitudinal surface temperatures over the seasons of thirty Titan years in order to better pinpoint the effects of coupling topography with the atmospheric model. We find that the influence of topography on the atmosphere results in differences in seasonal climates at the poles. The results show that the equatorial regions of higher elevation in our topography run experience lower surface temperature. This is due to the lapse rate. In the atmosphere, we have an equilibrium surface temperature, which is a balance of incoming and outgoing fluxes of heat. In the mountains, represented in green in Figure 5B and labeled in Figure 3, the surface will be cooler, as there is less air and less pressure above it. In low basins, such as the red areas in the height map (Fig. 5B) the surface will be hotter as the air there is under more pressure and experiences more weight from the air above it.

Impact on seasonal climate

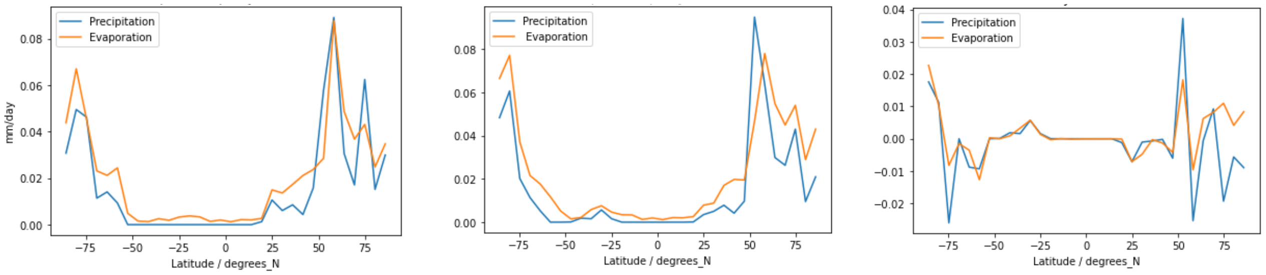
Our simulations show that the surface heights on Titan generate surface temperature cooling in the equatorial regions and midlatitudes on a scale of up to approximately -0.26K. This cooling is unlikely to produce new patterns of surface deposits, as very little rain falls in these regions.

The topographic features generate a yearlong warming effect of up to 0.28K poleward of 60°N, a minor yearlong warming effect of up to 0.18K between 25°N to 50°N, a minor cooling effect of about -0.26K in the Northern summer exclusively at 50°N, and a more pronounced warming of the surface of up to 0.52K equatorward of 50°S. These changes persist through most of the year, except for the cooling effect at 50°N.

Warmer summers

Overall, we find that coupling topography with the atmospheric climate creates a warmer northern summer and significantly warmer southern summer. In the next section we discuss how this leads to new hydrologic patterns in the balance of precipitation and evaporation.

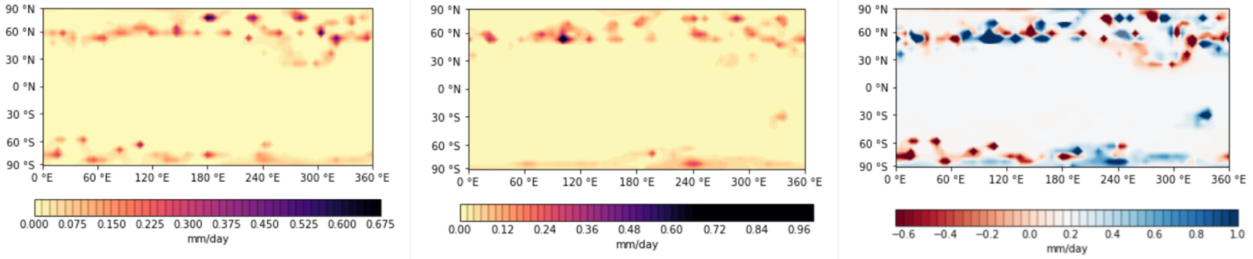
SPATIAL PATTERNS OF PRECIPITATION AND EVAPORATION



(A) CONTROL **(B) TOPOGRAPHY** **(C) DIFFERENCE (B - A)**

Figure 10. Precipitation (P) and evaporation (E) per day by latitude averaged over Titan years 121-150. (C) shows difference between simulations. Latitudes where the orange line overtakes the blue line show the topography simulation losing surface methane relative to the control. This trend occurs at both poles but is especially strong in the north due to significant increases in evaporative strength poleward of 50°N.

(A) CONTROL, daily P **(B) TOPOGRAPHY, daily P** **(C) Difference in Precip (B - A)**



(A) CONTROL, daily E **(B) TOPOGRAPHY, daily E** **(C) Difference in Evap (B - A)**

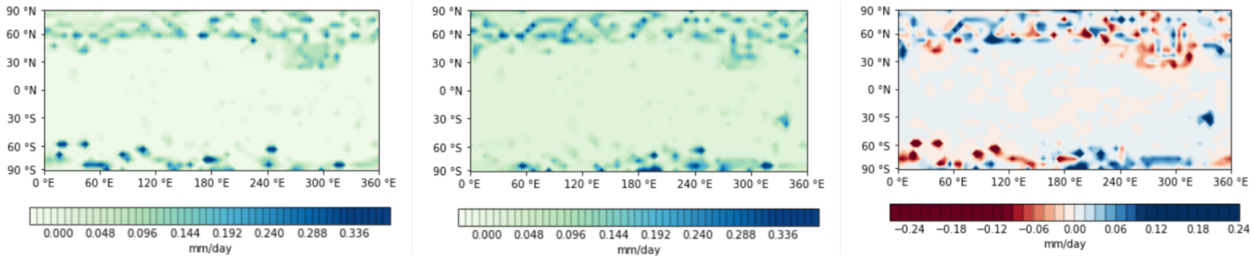


Figure 11. Equicylindrical projection of precipitation (P) and evaporation (E) per day averaged over Titan years 121-150. Color bars are scaled to the same minimum and maximum by color for the P distribution in both runs, and likewise for E.

NET PRECIPITATION

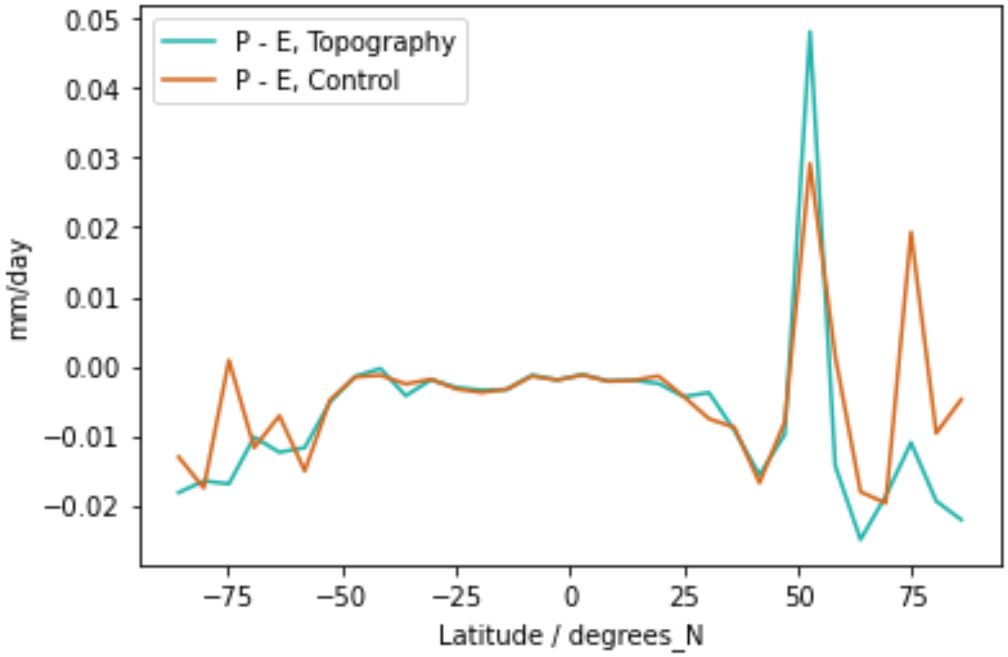


Figure 12. Net precipitation (P – E) per day by latitude averaged over Titan years 121-150. At latitudes where the green overtakes the dark orange line the coupling of topography with the climate system has caused an increase in surface methane relative to the control. At latitudes where the green falls below the orange line the topography has caused a decrease in the net precipitation.

P – E

Our GCM includes two systems of evaporation: Groundmethane evaporation from the subsurface and methane evaporation from the surface liquids. Surface evaporation takes into account evaporation from the surfaces of seas. The above figures reflect a combined total evaporation from both these dimensions. Deposits of surface liquids are caused by a net gain in P – E over the course of a Titan year, plus influences from surface hydrology. Our results show that warmer polar summers driven by the coupling of topography with the climate system causes more evaporation at the poles.

Methane transport and asymmetry in control run

Looking first at the control run's evaporation and precipitation in Figure 10a and the shape of the control simulation's results in Figure 12, we see how net precipitation in the control run generates the resulting surface liquid deposits at -75ºN (75ºS) and between 60°N and 90°N. In our mostly stabilized simulation results (in which overall hemispheric patterns have been pronounced and visible for at least 50 Titan years), liquids are efficiently transported away from the midlatitudes and preferentially distributed to the northern polar region. This occurs even when the lower atmosphere is not coupled to topography.

This contradicts the findings of Tokano (2019). In our model, our control simulation is governed by various climate processes including present-day orbital configurations (including eccentricity), topographic influence on the GCM's surface hydrology, and accurate wind behavior and temperature gradients. We find that coupling topography with the atmosphere is not solely responsible for asymmetric climate patterns and surface methane distribution.

Topography run: More active hydrologic cycle and loss of polar methane

In the run where topography is fully coupled to climate processes, the simulation reproduces similar behavior in equatorial areas and midlatitudes: no perennial buildup of surface methane occurs over any decade. When Titan's topography is allowed to interact with the climate system, the low surface heights at the poles and the high surface heights in the equator and mid-latitudes (Fig. 5b) generate yearlong polar surface temperature increases and patterns of drying (E>P) in both polar regions (Fig. 9c, 10b, 10c). The hydrologic pattern is also more vigorous in the topography run. There is overall more precipitation (Fig. 10) and more evaporation.

Rates of evaporation compared to precipitation increase compared to the control between 60°N and 90°N (Fig. 10b, 12). In northern latitudes poleward of 60ºN we observe shrinkage of basins including Punga Mare, Kraken Mare, Ligeia Mare, and Kivu Lacus. But there is slightly less evaporation than precipitation at 50°N. Over time this leads to creation of a new northern lake, 60m deep, not observed in the control simulation. In the far northwest region (20°E) we see slightly more wetting and less evaporation (Fig. 11a, 11b). The northeast, polar northwest, and south polar regions see drying patterns. Drying correlates with the exact location of low topographic features.

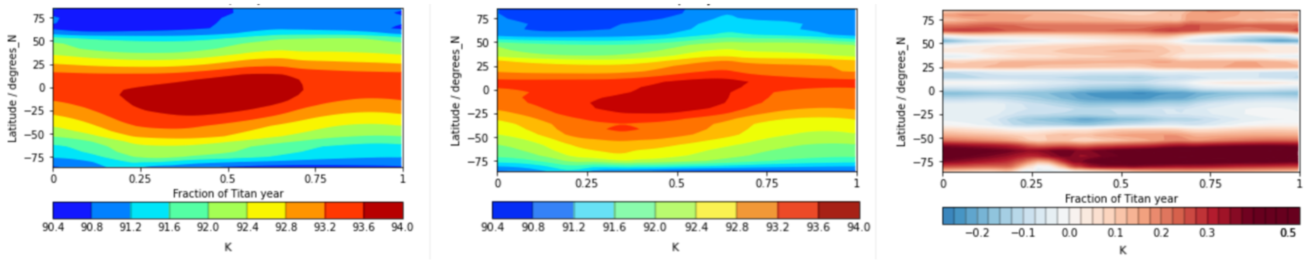
Due to the stronger southern summer, caused by Titan's low-lying topography in the south (the overall lowest point on the moon), there is more evaporation poleward of 60°S, which prevents the buildup of the minor lake shown in the control (equivalent, depth-wise, to the disappearance of Seattle's Lake Washington).

Topography influences spatial hydrologic features

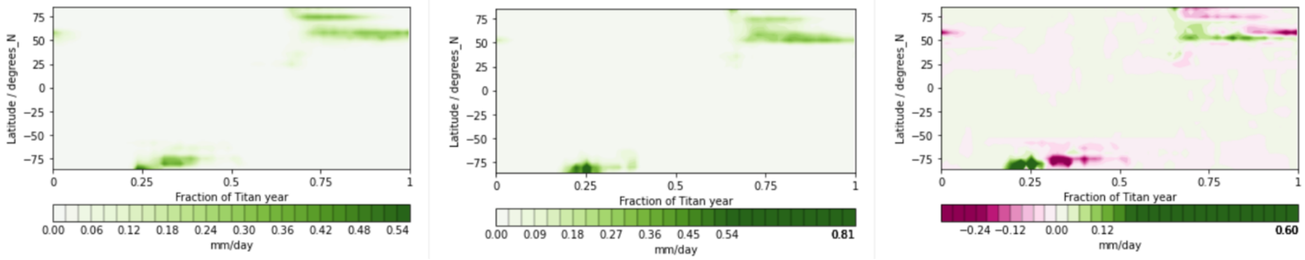
In summary, topography is essential in the design of a nuanced model of spatial weather patterns and hydrology. The low-lying topography in the north causes a warmer northern summer that does not allow as much methane to accumulate in the north. The significantly warmer and shorter southern summer created by deep, low-lying topographic features leads to the drying out of the southern poles. The effect may be even greater over a longer simulation timescale. Overall, net drying increases due to lower topography in both poles.

SEASONAL PATTERNS OF PRECIPITATION AND EVAPORATION

(A) CONTROL, surface temp **B) TOPOGRAPHY, surface temp** **(C) Difference in surf temp (B - A)**



(A) CONTROL, seasonal P **B) TOPOGRAPHY, seasonal P** **(C) Difference in Precip (B - A)**



(A) CONTROL, seasonal E **B) TOPOGRAPHY, seasonal E** **(C) Difference in Evap (B - A)**

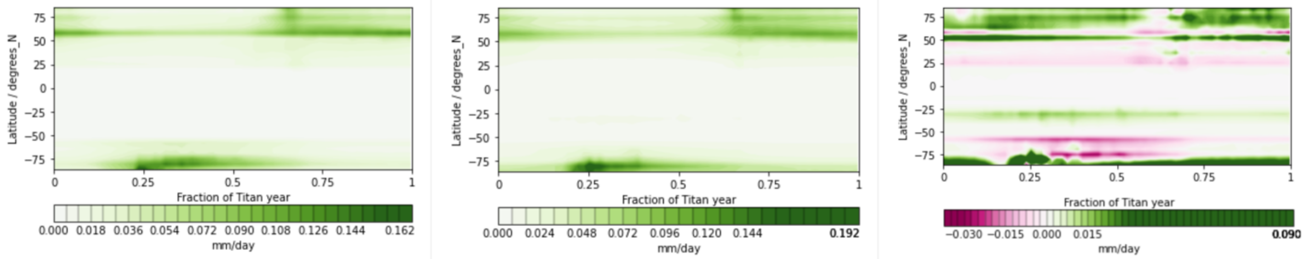


Figure 13.1. Seasonal zonal means over Titan years 121-150. Row 1: Mean seasonal surface temperatures over the course of one Titan year. Row 2: Precipitation zonal mean over the course of one year. Row 3: Evaporation zonal mean over the course of one year. The third column is difference between simulations.

Our results show how seasonal climates significantly change as a result of topographic influence on the latitudinal surface temperatures:

Precipitation

Topographic coupling to the atmosphere causes the southern precipitation season to occur earlier in the year. It becomes almost twice as strong in mm/day and this increase is strongest in the *first half* of the season (Fig. 13c). This is due to the increase in surface temperatures caused by the low-lying topography in the south (which includes Titan's lowest point).

In the northern hemisphere precipitation overall decreases and peaks a little later in the year (Fig. 13). There is less summer precipitation at the highest latitudes (75-90°N), which contributes to the shrinkage of polar lakes and seas (Fig. 13). This combines with the stark increase in northern evaporation and leads to the overall northern drying that we observe. But there is more precipitation at about 50°N (which supports formation of the new northern lake discussed) where there is a slight cold band of latitudinal temperatures.

Evaporation

Evaporation is strengthened throughout the year in regions where there are surface liquids that can evaporate (Fig. 13). (Times with less/no precipitation, such as the late southern summer, experience less evaporation, as reduced surface methane is available.) Evaporation increases dramatically throughout the entire year directly at the south pole.

Between 50-90°N, evaporation is also stronger nearly year-long, due to the influence of low surface heights on the atmosphere.

Latitudinal banding

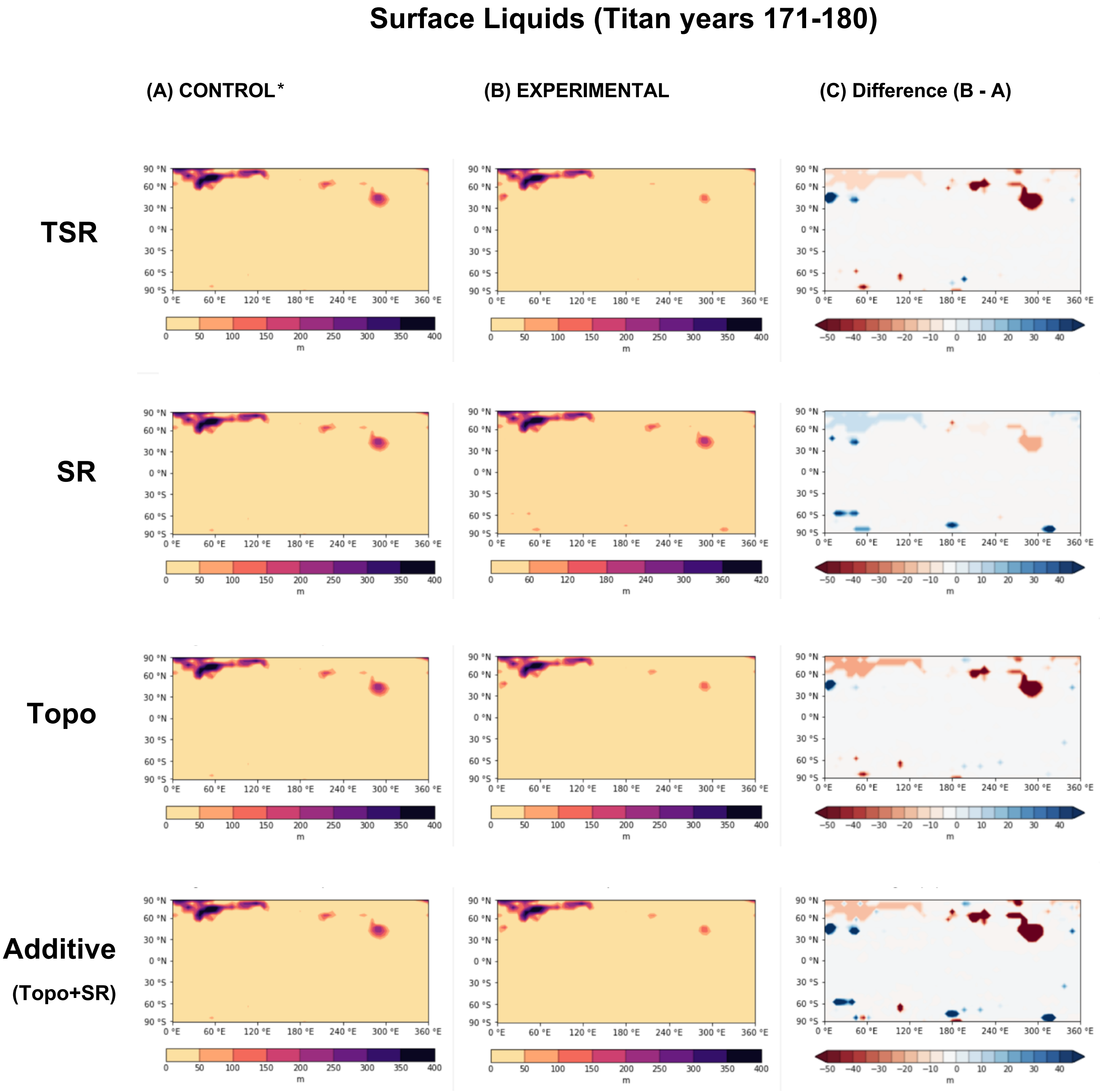
Evaporation increases are strongest and most concentrated at the latitudes where the lowest extremes in Titan's topography exist: 50°N, 75°N, and 60-80°S in the south polar region (Fig. 5B). There is also a minor band of increased evaporation at

30°S, where there is a slight anomalous low geographic area in an otherwise mountainous region (Fig. 3).

A trend of cooler temperature in the northern summer occurs along a specific band (50°N) where the highest point in Titan’s topography exists (Fig. 3, Fig. 13). This leads to a slight cooling effect and the thin band of increasing precipitation, which stays locked at that latitude and does not extend all the way to the pole.

We see the latitudinal bands most clearly in Fig. 13. In summary, it may be possible that microclimates are forming at these latitudes due to the strong impact of topographic extremes in those areas.

ITERATIONS WITH SURFACE ROUGHNESS



Surface Liquids (Titan years 171-180)

(A) CONTROL*

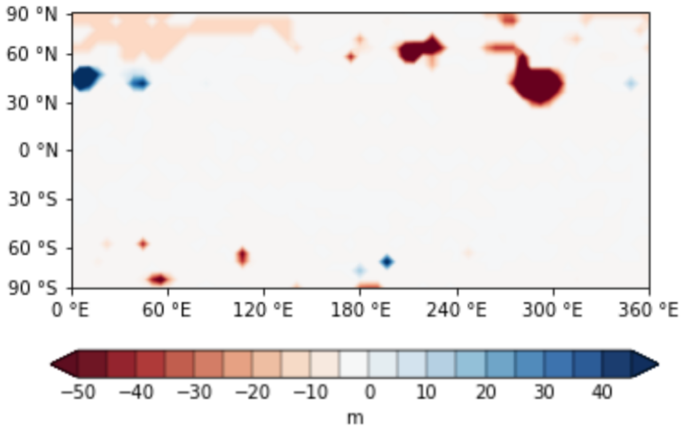
(B) EXPERIMENTAL

(C) Difference (B - A)

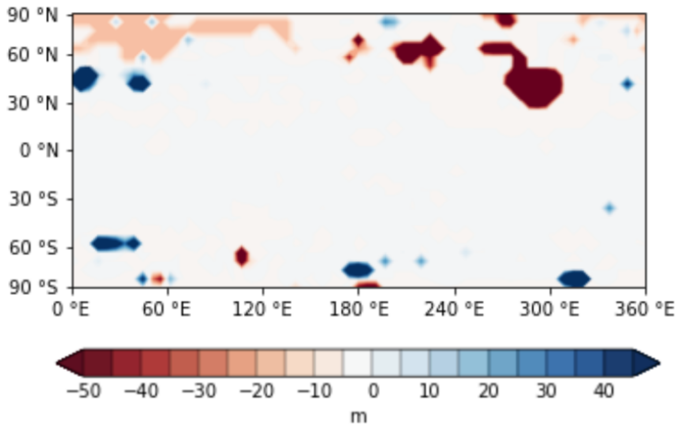
Figure 14. Surface liquid distribution for three simulations and a comparative analysis, averaged across Titan years 171-180. TSR: observed topography and estimated surface roughness are added simultaneously to the climate model and allowed to interact. SR: Only surface roughness added to climate model. Topo: same as in previous sections. Additive: Outcomes of isolated “topo” and “SR” simulations are added to compare their cumulative effect versus TSR. Dark red and blue represents >50m of methane change.

** Control is the same in all simulations. It’s replicated down the column as a visual aid.*

(1) TSR: Changes in TOPO+SR combined run compared to CONTROL



2) Changes in (Isolated TOPO + Isolated SR, manually added) compared to CONTROL



(3) Comparison of the above (TSR – Additive)

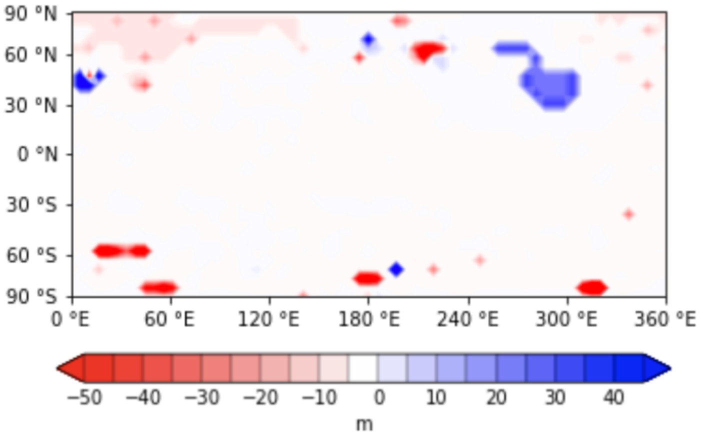


Figure 15. Changes in surface distribution of liquid methane by Titan year 180. The final row shows the gap between the simulation with topography and surface roughness added simultaneously, compared to adding isolated outcomes. Saturated reds and blues in the "comparison" represent >25m of methane change in the comparison.

A secondary parameter we also tested was surface roughness (Fig. 6). The surface roughness data for the model[16] was generated through an analogy to roughness lengths for similarly classified geomorphological features on earth. On Titan, we estimate that surface roughness may tend to be highest in the mountains and near the margins of observed seas, and that it may be lowest near dunes and on the very surface of the basins (Fig. 3, Fig. 6). Surface roughness lengths influence wind velocities in our GCM and influence the interaction of Titan's surface with the lower atmosphere.

Simulations

Figure 14 shows the outputs of this model[17]. In the Topography and Surface Roughness "TSR" simulation, observed topography and estimated surface roughness are added simultaneously to the climate model and allowed to interact. In the Surface Roughness "SR" simulation, only surface roughness is added to the model. The "Topo" simulation is the same simulation as in previous sections, run out to Titan year 180.

The "Additive" row is not a simulation. The outcomes of isolated "topo" and "SR" simulations are added to compare their cumulative effect versus TSR. Dark red and blue in Figure 14 represents >50m of methane change.

Impact of high SR

Areas of high SR near the *margins* of observed seas slightly increase surface methane in the entire NW region (in contrast with the dramatic northern loss in "Topo"), on a scale of 10-25m. High SR in the north also creates two new lake deposits of >50m depth (Fig. 14).

SR is very high in the southern hemisphere and southern pole (Fig. 6). As a result, the southern region has large gains in precipitation (not shown) and sees the creation of a few new deposits of southern surface methane of >50m depth. This is a departure from our Topo simulation's drying effect in both regions.

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[16] In Figure 6, the areas of highest SR are represented in orange, and areas of lowest SR are represented in purple.

[17] As before, in all three of these simulations and their "control" run, observed topography governs the horizontal transport of surface fluids.

In the SR run, surface methane loss only occurs in the Northeastern region of 30-60°N, 300°E. The region has some of the lowest roughness lengths. We can infer that surface roughness can indeed have an important impact on the distribution of surface liquids: high surface roughness leads to increased surface methane deposits, and low surface roughness may lead to loss in methane deposits.

Running SR and Topo together

When we add topography to the model *alongside* SR (TSR), we find that the impact of the very low basins in the north and south outweigh the impact of the estimated range of high SR in that region. The methane increase from high SR is diminished or reversed in northwestern areas surrounding Kraken Mare, and in most of the south.

Isolating the interaction of SR and Topo

Next, we aim to understand the interaction of topography and surface roughness with one another. We calculate the outcome of the isolated Topo + isolated SR (Additive) and compare that to interactive TSR run. Figure 15 pinpoints the impact of their interactions. In TSR (row 1), we see that southern low topography and high roughness counteract each other, but topography's influence wins out, eliminating the basins in the south. In the Additive (row 2), southern basins remain.

In the bright red areas of the "comparison" plot (row 3) we see where low topography and high SR interact: the scale of low topography cancels out high SR's effects completely. In bright blue areas, we see how low topography and *low* surface roughness interact: this interaction increases methane gain (row 3) more than when we sum low topography and low SR acting in isolation (row 2).

Summary

We can infer that when both are included simultaneously, topography and SR may have interesting impacts on the modeled weather and hydrology in a region. In Titan's southern areas of low topography and high SR, low topography has a cancelling or dampening effect on high SR's net wetting effect. But in one northern region with high SR in a latitudinal band of higher topography (50°N), the net wetting seemed to be cumulative. In future analyses, it would be interesting to see if these changes are most driven by seasonal precipitation or evaporation changes.

In future studies it would also be interesting to see just how *skewed* this relationship is in favor of SR or Topo. Are there medium topography heights in which SR would win out? Are there intensities of SR where SR would have a more prominent effect? How do these combinations influence weather if applied to different latitudes, and could this be an analogue to specific features on Earth? Answering these questions will give us a better sense of how SR might be tuned, added to future Titan models, and whether it may help us more accurately model large-scale climate features of other planetary bodies.

HOW DOES OUR RESEARCH COMPARE WITH TOKANO (2019)?

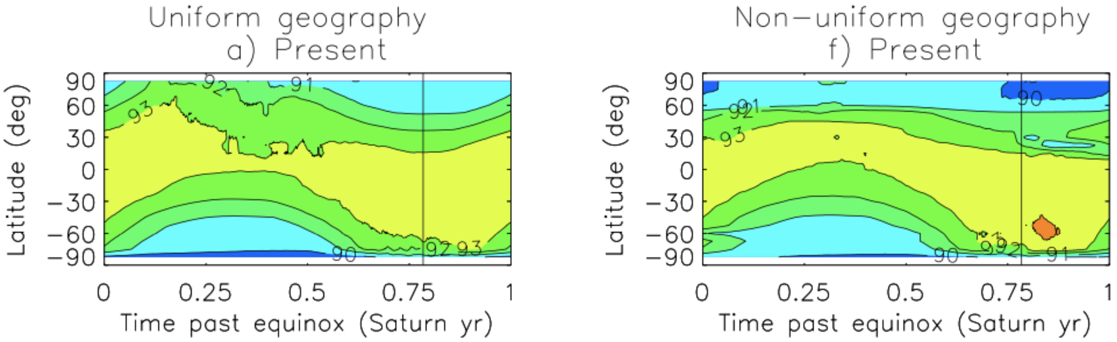
Key differences

Overall, our simulations contradict the findings of Tokano (2019) and test the power of our GCM with surface features coupled to the climate. We are able to reproduce observed spatial distributions of surface deposits in our various simulations, and we also show the potential relative impact of coupling topography, surface roughness, or their interactions, to the climate. We find that the coupling of topography with the atmosphere does not create the asymmetry that Tokano (2019) describes: instead of increasing northern methane deposits, we find that it creates more evaporation at both poles.

Potential causes

There are a few factors that may explain why our GCMs have diverged. First, Tokano's model is run for 9 Titan years total. We found this length of time inadequate in our own runs at producing stable balances between the atmosphere/surface/ subsurface reservoirs. Surface hydrology was still in flux at that point. Ours are run for roughly fifteen to twenty times as long in total (150-180 Titan years), increasing reliability.

Second, Tokano's model has documented inaccuracies in temperature and wind behavior (Lora et al. 2019), which in turn governs the transport of liquids. We find that the seasonal surface temperature patterns in our model govern hydrology, and the divergence in Tokano's seasonal temperatures and ours may explain a good deal of the differences. The Köln GCM's northern summer becomes cooler under the influence of topography and cooling persists year-long. Yet our model finds the opposite: we have net warming in the north due to low topographic heights, and only a temporary and very narrow band of northern cooling at 50°N.



Tokano's surface temperatures. Net cooling in the north (opposite of our results) and net warming in the south (similar to ours).

Additionally, Tokano found that when topography is added to the model, annual precipitation in the north polar region always exceeds that in the south polar region by a factor of at least *three*, regardless of what orbital settings are applied (Tokano 2019). We find this precipitation pattern not to be the case in our own simulations, likely also owing to the thermal differences between our simulations. Additionally, in his control run, Tokano has only southern methane. We also find this to be inaccurate; other parameters of the climate system (as shown in our GCM, and those of other teams) should be able to reproduce the deposits of northern methane.

Third, the inclusion of surface hydrology in our climate model is a key difference from Tokano's GCM. Our surface hydrology includes infiltration, groundmethane evaporation, and surface and subsurface flow, which are fundamental to replicating Titan’s observed surface liquid distribution and other aspects of its climate system (Faulk et al. 2020).

Tokano’s inaccurate modeling of winds and temperature (Lora et al. 2019) and lack of a surface hydrology scheme (Faulk et al. 2020) could have contributed to the discrepancies between Tokano’s 2019 seasonal patterns and ours, which then ripple throughout the conclusions of both models.

SUMMARY

In this thesis I first compare two topographical simulations: one where the observed topography governs only the GCM's surface hydrology, and another where the topography also interacts directly with the GCM's atmosphere to produce climate patterns. Contrary to Tokano (2019) we show that coupling of topography with the atmosphere is not solely responsible for asymmetric climate patterns and surface methane distribution. In both our simulations, the climate system efficiently transports methane to northern regions. We find that Titan's topography interacts with the lower atmosphere to cause polar increases in seasonal heating relative to the control simulation. This leads to warmer northern summers and significantly warmer and shorter southern summers. At both poles net evaporation increases, and surface methane buildup is reduced. We also observe the potential formation of a new northern lake and the disappearance of previous southern lakes.

In a third simulation, we also included surface roughness in the model, which resulted in the net wetting of northeastern and southern regions and the creation of new surface deposits. When included cumulatively with topography we observed that interaction between low surface heights and high surface roughness dampened this effect in the polar north and south. Conversely, the interaction between low surface height and *low* surface roughness resulted in heightened wetting of a northeastern basin.

In summary, our findings have broad implications: surface features are vital in the design of high-accuracy Titan GCMs. While unlikely to produce Titan's vast asymmetry in polar deposits in isolation, surface features create a non-neglible impact on the atmosphere and should be factored into the design of future Titan GCM experiments.

Brief summary of findings:

1. The coupling of topography with the climate system does not create the asymmetry in methane deposits, contrary to the conclusions of Tokano (2019).

2. However, the coupling of topography with the climate system causes significant changes in surface methane buildup: the polar regions exhibit less surface deposits.
3. The interaction of topography and the atmosphere alters surface temperatures. This drives a warmer southern summer and warmer northern summer, creating more evaporation in the poles.
4. The coupling of surface roughness with the climate system in isolation leads to wetting and the creation of new lakes in both poles. However, the interaction of topography and surface roughness together dampens much of this effect.
5. Inclusion of specific surface features, such as the depth of basins, distribution of specific mountains, and surface roughness, may govern the creation or disappearance of entire lakes/seas.

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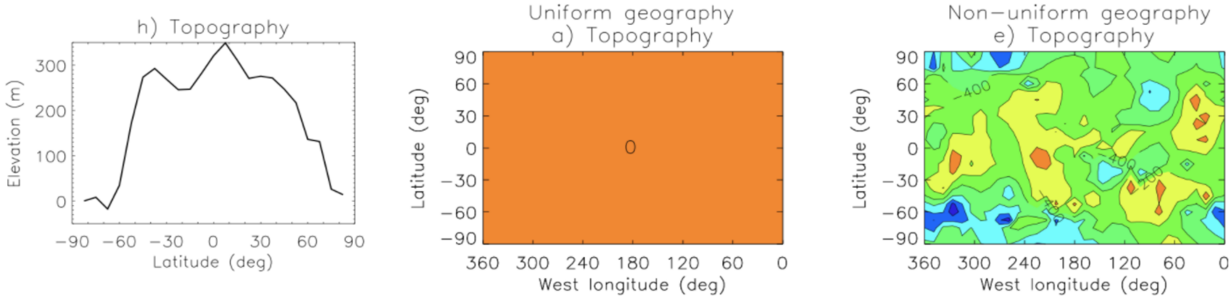
I'm grateful to my parents for sparking my love of learning many unrelated things and multitasking without end, and my fiancé Henry for keeping me company, cheering on my pursuit of a second major, and being the best source of encouragement as I (finally) completed my degree. I'd also like to thank my very own "Cassini": our three-year-old Shetland sheepdog who explores our pale blue dot incessantly and teaches me lessons each day through his boldness and curiosity.

APPENDIX / Other Figures



Tokano creates a "uniform geography" simulation and a "topography" simulation. This series of images shows the difference in the topographic height between the northern and southern latitudes. Source: Tokano, 2019

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