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Large catchment area recharges Titan's Ontario Lacus

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ABSTRACT

We seek to address the question of what processes are at work to fill Ontario Lacus while other, deeper south polar basins remain empty. Our hydrological analysis indicates that Ontario Lacus has a catchment area spanning 5.5% of Titan's surface and a large catchment area to lake surface area ratio. This large catchment area translates into large volumes of liquid making their way to Ontario Lacus after rainfall. The areal extent of the catchment extends to at least southern mid-latitudes (40°S). Mass conservation calculations indicate that runoff alone might completely fill Ontario Lacus within less than half a Titan year (1 Titan year = 29.5 Earth years) assuming no infiltration. *Cassini* Visual and Infrared Mapping Spectrometer (VIMS) observations of clouds over the southern mid and high-latitudes are consistent with precipitation feeding Ontario's large catchment area. This far-flung rain may be keeping Ontario Lacus filled, making it a liquid hydrocarbon oasis in the relatively dry south polar region.

1. Introduction

With a thick atmosphere, a methane-based hydrological cycle, stable bodies of standing fluid at its surface, and many active surface processes, Saturn's largest moon Titan is surprisingly Earth-like. The pressure-temperature conditions (1.4 atm, 90-94 K) (Fulchignoni et al., 2005) are close to the triple point of hydrocarbons (e.g methane's triple point is ~92 K). Hence, hydrocarbons play the same role on Titan as water plays on the Earth. The movement of fluid on the surface has created fluvial networks and valleys (Porco et al., 2005; Elachi et al., 2006; Barnes et al., 2007; Jaumann et al., 2008) which have been extensively observed and studied (Perron et al., 2006; Burr et al., 2013) by the *Cassini* mission. Titan's surface conditions therefore make it the only known extra-terrestrial planetary body to currently have an active surface hydrology governed by an Earth-like hydrological cycle.

As a result of this cycle, Titan has lakes and seas of hydrocarbons at its poles (Stofan et al., 2007). However, the exact composition of the liquid for any given lake is not well known. Thermodynamic models estimate lake composition using *in situ* observations from the *Huygens* probe (e.g. Cordier et al., 2009). This model led to the conclusion that the lakes consist mostly of ethane, with lesser amounts of methane (10%) and propane (7%) along with other hydrocarbons. The discovery of ethane in Ontario Lacus based on VIMS observations (Brown et al., 2008) is consistent with the model predicted composition of lakes.

However, recent observations reveal that one composition model does not fit all liquid bodies. Bathymetry studies (Mastrogiuseppe et al., 2014; Le Gall et al., 2016) and lab based experiments (Mitchell et al., 2015) indicate that the northern sea Ligeia Mare has a composition of nearly pure methane. Lorenz (2014) suggests that composition varies across Titan's seas due to the differing solute abundance because of latitude dependent precipitation and evaporation. MacKenzie and Barnes (2016) also find that the evaporite configuration of different lakes varies thereby indicating potentially different bulk composition of the lakes. These findings reinforce Lorenz's idea of latitude based precipitation and evaporation (or some similar latitudinal influenced mechanism) leading to diverse composition of the hydrocarbon lakes and seas. In spite of these developments, the precise bulk composition of these lakes still remains indeterminate.

The mechanism driving spatial distribution of the lakes on Titan's surface is also not well understood. While many lakes dot the north polar region of Titan (Stofan et al., 2007; Sotin et al., 2012) it is perplexing to see an almost barren south polar region. The south polar region is devoid of liquid except four small lakes and one large lake, Ontario Lacus. Ontario Lacus was the first fluid body observed by *Cassini* mission using the Imaging Science Subsystem (ISS) instrument (Turtle et al., 2009). Several studies have been carried out to interpret its composition (Brown et al., 2008),

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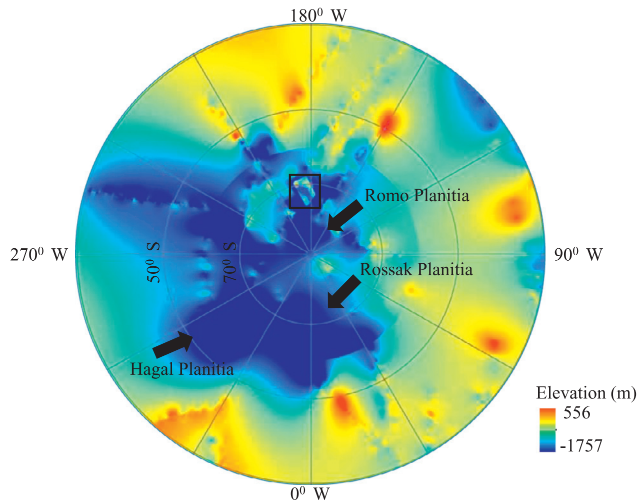

Fig. 1. Titan's global topographic map derived by Lorenz et al. (2013) in Polar stereographic projection. Ontario Lacus is located within the region marked by the black box. The black arrows indicate the other low elevation regions in the south pole that are empty. The seams in the image are the available topography information while the rest of the topography is generated by an interpolation procedure due to the absence of global topographic data. The spatial sampling is 22 km (0.5°) per pixel.

smoothness (Wye et al., 2009; Cornet et al., 2012b), and its bathymetry (Hayes et al., 2010).

Ontario Lacus measures 235 km × 75 km (Wall et al., 2010) with surface area of ∼16,200 km^2. The other four small lakes (Wood et al., 2013) in the south polar region are Crveno Lacus (∼32 km × 24 km), Shoji Lacus (∼6 km × 6 km), Tsomgo Lacus (∼53 km × 15 km), and Kayangan Lacus (∼9.5 km × 9.5 km). Some large basins near the south pole of Titan exist at lower elevations than Ontario Lacus, but remain empty currently. Fig. 1 shows Hagal, Rossak, and Romo basins, along with Ontario Lacus' basin.

Ontario Lacus is readily recognizable in the south polar region by its shape which resembles a right human footprint (Fig. 2). The morphology of Ontario Lacus tells a story of active processes. Mountains surround the northern end of Ontario Lacus and rise to heights of ∼400 m. The lake's western shore hosts a delta-like morphological feature (Wall et al., 2010) at the end of Saraswati Flumen, a very long channel (300 km) distinctly observable in the RADAR data and as shown in Fig. 2B and 2C by arrows. A bay exists along the eastern shoreline which has likely been modified by fluvial processes (Wall et al., 2010). The southeast corner of Ontario Lacus shows a bathtub ring of evaporite (Barnes et al., 2009; Cornet et al., 2012a; MacKenzie et al., 2014). These processes collectively indicate that Ontario Lacus likely represents a dynamic hydrological system. Earlier studies (Cornet et al., 2012a; Hayes et al., 2010) suggested that Ontario Lacus lies in a shallow depression but more recent bathymetric studies by the radar detection of a lake-bottom reflection indicate that the depth could be as much as ∼90 m in some places, with an average depth of ∼50 m (Mastrogiuseppe et al., 2016).

Aharonson et al. (2009) proposed that the asymmetry in the liquid distribution between the north and south pole may be due to the long term climate variations caused by the eccentricity of Saturn's orbit around the Sun. This scenario has been further explored using General Circulation Models (GCM) (Lora and Mitchell, 2015). Although plausible, the lack of pervasive evaporite deposits at the south polar region (MacKenzie et al., 2014) does not align with these hypotheses. In either scenario, it is difficult to explain why Ontario Lacus, neither the lowest point of the south pole nor the largest basin, remains filled in an otherwise dry region. In this work, we address this question via a detailed hydrological analysis of Ontario Lacus using topographic and synthetic aperture RADAR datasets. The major objectives of this study are to identify and characterize the major drainage features around Ontario Lacus, and determine whether surface hydrology of the region around Ontario Lacus can shed light on why it is currently filled.

We discuss our three main analyses in the following sections. Section 2 discusses the analysis for catchment area using RADAR derived high resolution topography as well as low spatial resolution global topography (based on extrapolated data). In Section 3, we evaluate the feasibility and conditions for the fluid availablility at Ontario Lacus using a simple mass balance model utilizing current estimates of precipitation, evaporation and infiltration. Section 4 illustrates our stream profile analysis around Ontario Lacus aimed at understanding the hydrological evolution of the region which is followed by discussion and conclusions in Section 5.

2. Catchment area

Catchment area refers to the area from which rainfall flows into a river, or lake. It forms an important parameter to understand the surface hydrology of a region.

2.1. Method

We analyze the topography of the region around Ontario Lacus using ArcGIS to determine the extent of its catchment area. Sparse coverage of high resolution topographic data is an obstacle for our present day understanding of Titan. The extent of the available stereo-derived topography (1.4 km per pixel) data of our study area is indicated by a black outline in Fig. 1. These data provide the local scenario for the determination of the catchment area of Ontario Lacus. Details of the topographic mapping are discussed in Section 4.1.

To fill in the gaps of topography, Lorenz et al. (2013) interpolated a global topography map for Titan using SARtopo and altimetry data (Stiles et al., 2009). To test the validity of this approach (Lorenz et al., 2013) downsampled the Earth's topography data with the geographical distribution where Titan data are available and carried out a spline interpolation. The topography map generated all the major topographical features on the Earth except the Tibetan plateau. This indicates that Lorenz et al. (2013) interpolation technique captures the overall trend in topography(Fig. 3).

The global topography map has a resolution of ∼22 km per pixel, fifteen times coarser than the available high resolution stereo topography in the immediate vicinity of Ontario Lacus. Despite this difference, the interpolated map is useful as it provides the regional context necessary for estimating the catchment area contributing to Ontario Lacus. We re-interpolate these data using the Topo to Raster tool available in ArcGIS 10.1 (ESRI) to generate correct surfaces (Tarboton, 1997). The resulting topography map is used to determine the catchment area of Ontario Lacus as follows:

i We first remove depression artifacts or pixel-scale lows from the digital elevation model. These "sinks" are localized surfaces of internal drainage that do not drain anywhere and thus cause the algorithm to go into an infinite loop.
ii The algorithm then generates a flow direction raster where each cell drains or flows in a particular direction depending on the elevation of the surrounding terrain.
iii From the flow direction raster, we generate a drainage network map based on local flow accumulations.
iv We then place bucket points at the edge of an accumulation or at major confluences. Specifying a bucket point indicates the outlet of the catchment area into the lake or stream for calculating the total flux into the body.

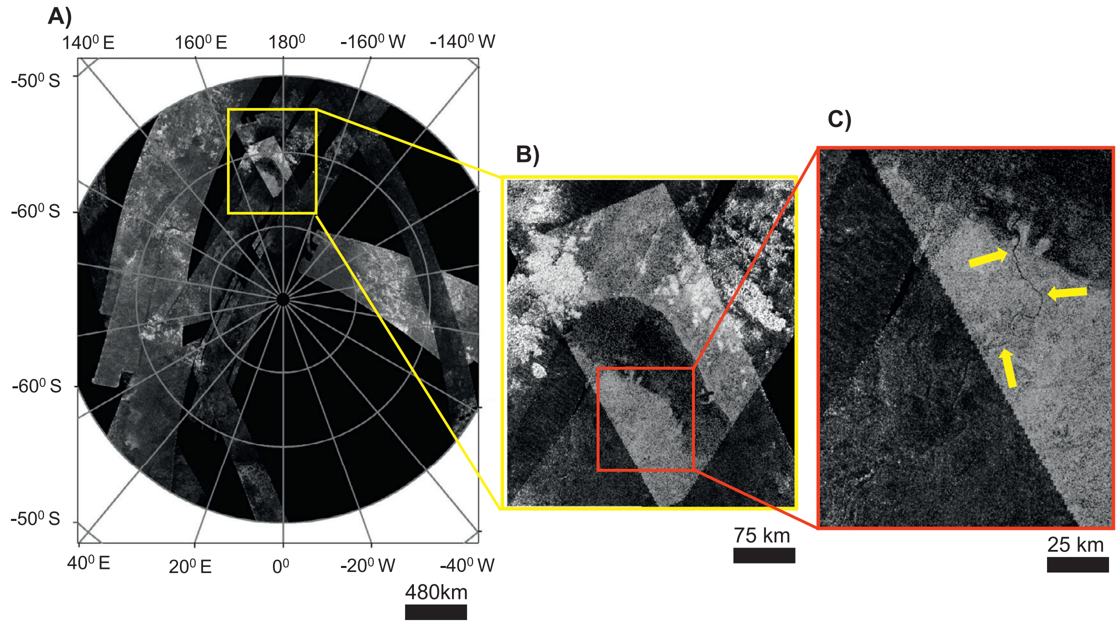

Fig. 2. The spatial extent of the study area and available data coverage. A) RADAR coverage for the south polar region of Titan, B) Ontario Lacus C) The longest stream in the region, Saraswati Flumen in the vicinity of Ontario Lacus creates a deltaic deposition (Wall et al., 2010).

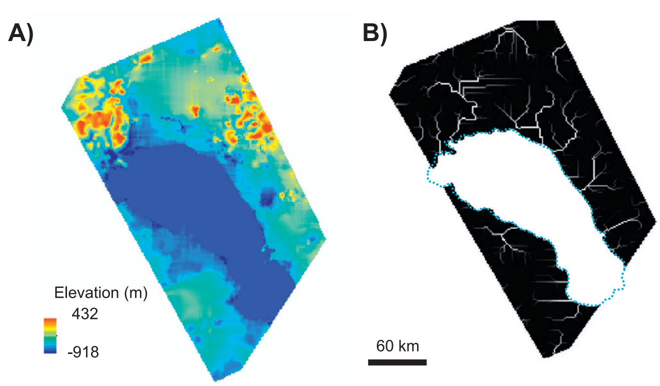

Fig. 3. A) High resolution stereo DEM acquired using the RADAR T57/T58/T65 stereo (1.4 km per pixel resolution) data. B) Flow accumulations (bright white pixels) calculated by ArcGIS' hydrology tool on the topographic data of Ontario Lacus. The white lines indicate regions where fluid accumulates. The blue dotted line demarcates the spatial extent of Ontario Lacus. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

We validate our results obtained from the global interpolated data by performing the above analysis on the high resolution but limited coverage topographic data around Ontario Lacus. Despite a fifteen times difference in resolution, the results from the high and low resolution topography data are consistent.

2.2. Results

The total catchment area of Ontario Lacus is shown in Fig. 4 and corresponds to an area of $\sim 4.6 \times 10^6$ km^2. The catchment is made up of two sub-catchment regions as shown in Fig. 4B: western sub-catchment (bound by thick line), and eastern sub-catchment (bound by thin line). The one towards the south (bound by dashed line) drains away from Ontarion Lacus and is not included. Based on the available topography data, the western and eastern sub-catchments drain into Ontario Lacus and so we have used the combined area of these two regions as the catchment of Ontario for our calculations. The RADAR images of the eastern sub-catchment indicate potentially high elevation regions (bright terrain in RADAR data) which might affect the contribution of this sub-catchment to Ontario. However, incomplete RADAR coverage over the eastern sub-catchment prevents a definitive determination of the drainage divide. While the catchment area estimates should be considered with some caution, broad scale topography of the region shows draining towards Ontario Lacus. Any small changes to the contribution will not drastically change our final interpretation.

To put this in perspective, Ontario Lacus is about the size of Lake Michigan. Yet, Lake Michigan has a catchment area of $\sim 0.11 \times 10^6$ km^2, one and a half orders of magnitude smaller than Ontario Lacus. 5.5% of Titan's surface area (8.3×10^7 km^2, assuming Titan is a sphere) is covered by Ontario Lacus' catchment area. We think this is substantial planetary coverage for a lake as big as Lake Michigan, whose catchment area covers only 0.02% of Earth's surface. Another Earth analog could be Lake Eyre in Australia, which sits in an endorheic basin (a drainage basin that doesn't drain into the ocean), like Ontario's, and covers 1/6th of the Australian continent. Lake Eyre has one of the biggest catchments of all the lakes on Earth, which at $\sim 1.2 \times 10^6$ km^2 is still just one quarter the size of Ontario's catchment. The evaporation rate and precipitation rate around Lake Eyre region are 0.2 m/Earth year and 0.25 m/sEarth year. For comparison, the evaporation and precipitation rate we use for Ontario Lacus are listed in Table 1.

The ratio of catchment area to surface area for a lake is a measure of inflow into the system. From our data this ratio for Ontario Lacus is 83 while it is 118 for Lake Eyre. Therefore in hydrological context, Ontario Lacus might be similar to Lake Eyre, although more arid. Despite being mostly dry, Lake Eyre basin still gets filled by periodic floods and groundwater recharge with varying amounts of fluid. Even a slight rainfall converts Lake Eyre into a semi-arid region. A similar increase in precipitation might result in filling of the paleo-basins on the south pole over geological time scales, however such an increase has not been observed during *Cassini's* lifetime.

We are unable to contrast the catchment area of Ontario Lacus with other deeper basins on the south pole due to poor altimetry coverage available in those regions. The interpolated global topography map is primarily derived from RADAR altimetry and SAR-

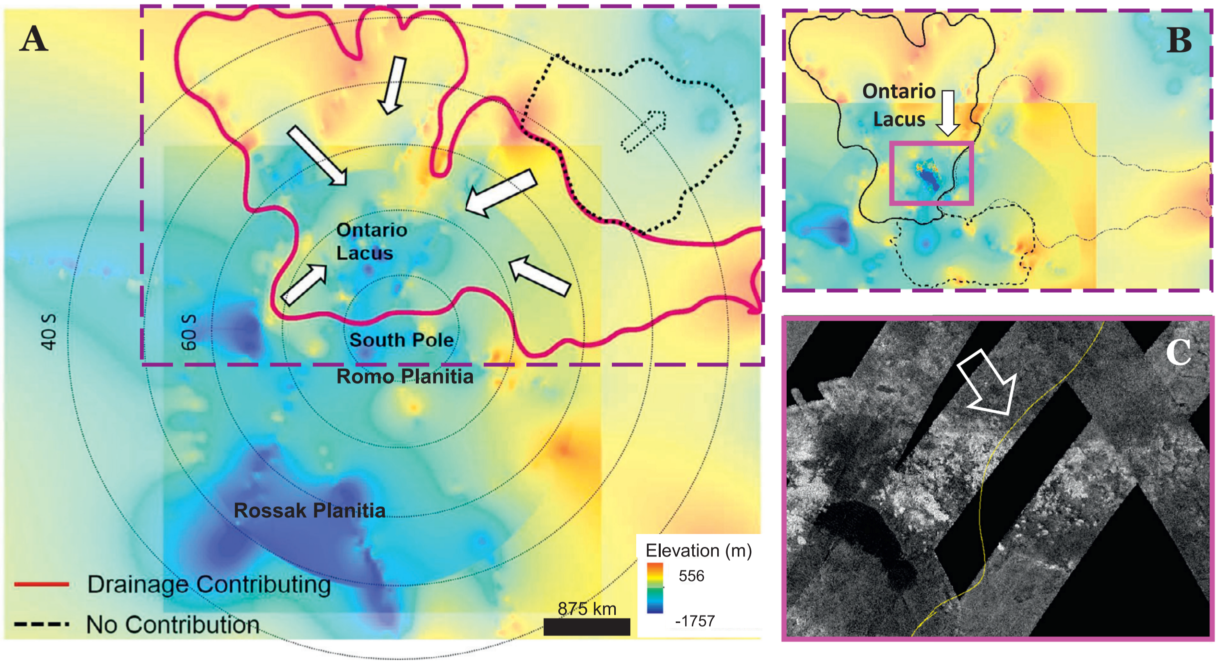

Fig. 4. A) Catchment area of Ontario Lacus (in polar stereographic projection) derived from hydrological analysis. The magenta extent marks combined catchment area that drains into Ontario Lacus. The black dotted line marks the region which does not drain into Ontario Lacus but its surrounding basins. The catchment regions are overlaid on the DEM of the region to provide the elevation context. B) The three major catchment regions of Ontario Lacus (see Discussion section). Solid line shows the catchment that distinctively contributes to Ontario Lacus. The faint line to its right shows the catchment that might not directly contribute to Ontario but is inferred based on regional trends. The dotted line in B) shows the catchment that does not contribute to Ontario. It drains into the Romo Planitia, close to the south pole. C) RADAR image of a section of the catchment area (boxed area in B) indicating a potential drainage divide (shown by white arrow) which might affect the total catchment area of Ontario Lacus.

Table 1
List of the parameters used in the mass balance study for Ontario Lacus.
* based on Mitri et al. (2007) ** based on Schneider et al. (2012).

Ontario	Semi Minor Axis	75 km
	Semi Major Axis	235 km
	Area	16,200 km^2
	Maximum Depth	0.09 km
	Maximum Volume	1,462 km^3
Result from 2.1	Total Catchment Area	4,600,000 km^2
Input for eqn 3	Precipitation Rate 1*	1.2 m/Titan year
	Precipitation Rate 2**	4 m/Titan year
	Evaporation Rate 1*	30 m/Titan year
	Evaporation Rate 2**	23.6 m/Titan year
Results from 2.2	Runoff 1*	5,440 km^3/Titan year
	Runoff 2**	18,400 km^3/Titan year
	Evaporative Loss 1*	1,660 km^3/Titan year
	Evaporative Loss 2**	1,300 km^3/Titan year

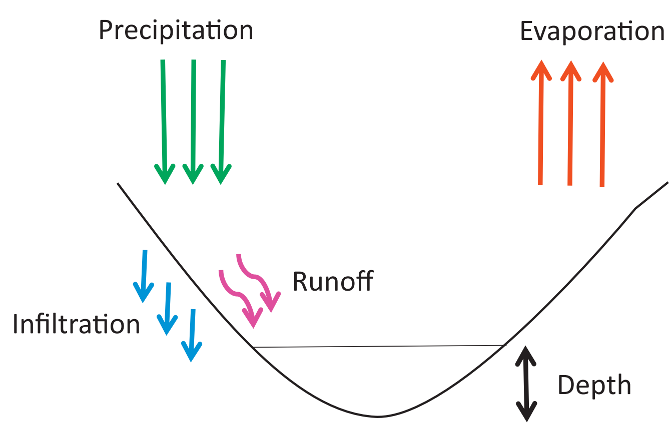

Fig. 5. A diagrammatic representation of all the hydrological parameters included in the mass balance calculations for Ontario Lacus.

Topo. Stiles et al. (2009) derived a technique for estimating topography using the overlap between each of the five radar beams that make up a SAR image, which he named SARTopo. Since Ontario Lacus has been well covered by RADAR strips we were able to extend our analysis to the surrounding regions. We were not able to derive any meaningful watersheds for the other basins using the global topography map. For the bigger seas on the north pole of Titan (Lorenz et al., 2013) roughly estimated the catchment areas as thrice the surface areas of the seas.

A future mission to obtain global topography with a resolution of ∼50 km would be required to do this task completely. It is perplexing that the other, deeper basins are closer to the pole and still remain dry which is in contrast to the latitude based precipitation suggested by GCM models like that of Schneider et al. (2012). However, its intriguing to note that the largest sea at Titan's North Pole is also farthest from the pole.

3. Mass balance

Our results from Section 2, namely the large catchment area for Ontario Lacus, motivate us to use mass balance calculations to try to understand the movement of fluids in the drainage system of Ontario Lacus. We do this by assuming conservation of mass flux and calculating the mass balance in/out of the system. The parameters of this model comprise of precipitation, evaporation, runoff and infiltration as shown in Fig. 5. The model helps us approximate how each parameter contributes in the fluid movement.

3.1. Method

We model incoming fluid accumulation and outgoing losses to determine whether a lake might be filled or empty.

$$\text{Change in the lake volume} = \text{Input} - \text{Loss} \pm \text{Sources or Sinks} \quad (1)$$

Input derives from the precipitation over the catchment area (calculated in Section 2.2). Loss occurs due to evaporation from the lake's surface. The difference between precipitation and infiltration (i.e the runoff) would eventually feed the lake. Ontario's surface area as determined using ArcGIS is ∼16,200 km^2 The depth of the lake has 90 m as an upper limit and 50 m as an average. We express this balance in the form of an equation:

$$\frac{\delta(HA_l)}{\delta t} = PA_c - EA_l \tag{2}$$

where H represents the depth of the lake, A_l, the surface area of the lake, P, the precipitation over the catchment area A_c, and E is the evaporation from the lake.

We assume that the lake is in a steady-state, i.e there is no change in the liquid level. We acknowledge that, since evaporites have been identified along the shoreline of Ontario Lacus (Barnes et al., 2009; Cornet et al., 2012a; MacKenzie et al., 2014), the lake level has definitely changed over geologic time. Furthermore, Hayes et al. (2010) and Turtle et al. (2011b) indicate that the lake level may have changed in *Cassini's* lifetime. Cornet et al. (2012b), however, suggests no change in Ontario Lacus' extent between 2005 and 2010. We proceed with the steady state assumption since the lack of gross variations places an upper limit on $\frac{\delta(HA_l)}{\delta t}$.

In the absence of knowledge of the porosity of Titan's surface (Hayes et al., 2008), we assume it to be impervious and as such our estimates are a maximum for runoff. Hence evaporation is the only process by which the system is losing liquid. The left hand side of Eq. (2) disappears under our steady-state assumption, reducing our model to:

$$PA_c = EA_l \tag{3}$$

Thus, the factors that determine whether Ontario Lacus remains filled according to this mass balance calculation are the contributing catchment area, lake's surface area, precipitation and evaporation rates.

3.2. Results

Precipitation into a catchment area determines the fluid input. We find the volume of the fluid input to Ontario Lacus as ∼5,440 km^3/Titan year based on precipitation rates from Mitri et al. (2007) and ∼18,442 km^3/Titan year based on precipitation rates from Schneider et al. (2012). While Mitri et al. (2007) uses a bulk aerodynamic model to get the precipitation and evaporation rate, the rates calculated by Schneider et al. (2012) uses simulations with a three-dimensional atmospheric model coupled to a dynamic surface reservoir of methane. Since the catchment area of Ontario Lacus is large (∼4 million km^2), it plays a major role in quantifying the fluid input. However, there are no firm estimates on either the evaporation or precipitation rates on the surface of Titan. So, we proceed further by utilizing the values from the literature to evaluate whether any of the lower or upper bounds scenarios (low precipitation, low evaporation and high precipitation, high evaporation) are consistent with our observational inferences assuming that rates of evaporation/precipitation are valid.

Comparing the estimated rate of fluid input volume (∼5,440 km^3/Titan year) with the volume of Ontario Lacus (∼1,462 km^3 as an upper limit corresponding to depth of 0.09 km) suggests that the lake would be filled in less than half a Titan year (1 Titan year = ∼29.5 Earth years) provided precipitation happens at the same rate that we use in our previous calculation of fluid input to Ontario Lacus and the lake starts empty. With the depth of the lake at an average of 0.05 km even less volume is needed. Therefore, when we use the average depth, precipitation floods the lake in one Titan year. Table 1 lists the parameter values that we use and the results that we get using the mass balance calculations.

Evaporation from the lake's surface accounts for the fluid loss from Ontario Lacus. Mitri et al. (2007) determines the evaporation rate as 11 m/Earth year (324 m/Titan year) for wind speeds of 1 m/sec. Since these wind speeds seem high for Titan surface conditions (Lorenz, 2014), we take the baseline value of 1 m/Earth year or 30 m/Titan year as the evaporation rate. We also use another value for evaporation rate, 23 m/Titan year (Lorenz, 2014), as an alternative lower value. The volume lost from Ontario's system amounts to be 1660 km^3/Titan year or 1306 km^3/Titan year depending on the evaporation rate we choose.

Thus, using the available evaporation and precipitation rates for Titan, the evaporation from Ontario Lacus' surface area would be smaller than the precipitation (over the catchment area) in our mass balance calculation. It follows that the input fluid volume to Ontario Lacus is larger than the fluid loss from the system by evaporation alone. These results complement our results of a sizeable catchment area (in Section 2) contributing fluid to Ontario Lacus. However, this consistency between observed inference and theoretical estimates should be treated with caution in view of the uncertainties associated with evaporation and precipitation rates. We certainly need more robust measures of these parameters from future missions to Titan.

4. Stream profile determination

We extract elevation profiles of some of the prominent streams in the area to compare their maturity levels or tectonic upliftments (Cartwright et al., 2011; Burr et al., 2013) around the region. A flatter stream profile generally indicates a matured stream that has worked its way over the bedrock by erosion and flow over a long time (Davis, 1899) assuming no tectonic uplift to rejuvenate the stream. In contrast, a stream profile with many knickpoints might indicate a tectonically active region (Wobus et al., 2006). Thus, observing the stream profile gives us insights into the hydrological evolution of the region.

4.1. Method

The high resolution digital elevation models (DEMs) on Titan are generated by stereoanalysis of overlapping SAR (Synthetic Aperture RADAR) swaths and are controlled to agree with altimetry and SARTopo data in absolute elevation (Elachi et al., 2004; Kirk and Howington-Kraus, 2008).

The DEM for this analysis was generated in two parts from the SAR image swaths taken on flybys T57 and T58 each combined with the swath from T65. Incidence angles in the stereo overlap vary from 38.5° to 45.3° (North to South) for T57, 25.7° to 34.5° (North to South) for T58, and 22.3° to 33.0° (West to East) for T65 flyby. Given that the pairs have almost perpendicular look directions, and using a matching precision of 1.4 pixel (250 m), the expected vertical precision EP (Leberl et al., 1992) ranges from 85 to 120 m, or an average around 100 m but with the south end (T58) generally being a little bit better. The DEM was produced in BAE System's SOCET SET stereo software package (Miller and Walker, 1993, 1995), using a rigorous sensor model for the RADAR SAR images.

Because of the difficulty of matching noisy radar images, the DEM was made by interactive measurement of a large number of ground points that were connected into a triangulated surface and then interpolated. The precision and accuracy of the altimetry are much better than the stereo precision, so the absolute heights in the DEM are only good to the ∼100 m level set by the stereo.

Using these DEMs we first map Karesos Flumen, Hubur Flumen, and Saraswati Flumen in the vicinity of Ontario Lacus. Then we extract the stream elevation profile from the high resolution topography data. A MATLAB-based algorithm convolves the accumulated

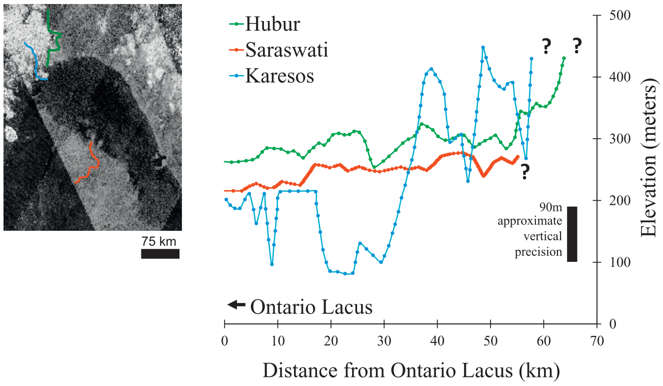

Fig. 6. The general topographic profile of a few streams around Ontario Lacus. A flat profile might indicate a mature stream with no tectonic uplift. As the profile suggests, Saraswati (in red) flumen is flatter, whereas the profile of other two fluminae, Karesos and Hubur (in blue and green respectively) are steeper – not too surprising as they originate in mountains. The abrupt changes in the profile of Karesos could be a topographical artifact because of coarse resolution topography data. However, the broad trend still suggests a steeper gradient of Karesos flumen compared to the other two fluminae. The inset shows location of these fluminae near Ontario Lacus in a RADAR map. The gentler gradient of Saraswati Flumen could also suggest that it has a much larger drainage with headwaters not covered by the limited DEM dataset. We indicate this absence of data through a question mark in the stream profile. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

flow at a given location with its elevation and flow direction to generate the profiles as shown in Fig. 6.

4.2. Results

The extracted stream profiles indicate that Karesos and Hubur Fluminae, which fall from the high northern mountains near Ontario Lacus have steep gradients. The elevation at the head of these streams extends as high as 400 m. The abrupt changes in the profile of fluminae are topographical artifacts because of coarse resolution topography data. In contrast, the western stream, Saraswati Flumen (the one associated with the deltaic deposition), has a much gentler gradient which suggests either a more developed fluvial system than the rugged mountains in the north or that the substrate beneath Saraswati is more erodible, consistent with its geological setting relative to the mountainous rivers. Alternatively, our observation of the gentler gradient could be due to a much larger drainage for Saraswati Flumen, with its headwaters invisible because they are unavailable in the SAR imagery. Since we carry out this analysis only on the high resolution DEM we are restricted by the available data. Hubur, like Saraswati, is a longer river, and thus the steeper part of the stream profile might not be available in our data for the mapping.

We also report the occurence of a putative oxbow lake along the path of Saraswati flumen in the RADAR data (see Fig. 7). Such features on Earth are associated with low gradient, sediment rich river systems. When a meandering river straightens its course the bend in the river is cut off from the flow, creating an isolated lake. Oxbow lakes are more frequently found in the course of alluvial rivers on Earth. The observation of a putative oxbow lake supports the idea that the western channel, Saraswati Flumen, might be an alluvial channel that experienced fluctuations in its discharge in the past. However, high resolution imagery data of the region is required to validate this observation.

In order to see the evolution of hydrological processes in Titan-like conditions we investigate how Hack's Law evolves on Titan's streams. Hack's Law (Willemin, 2000) relates the flow length of a stream to its contributing drainage area. If "L" is the length of the longest stream and "A", the catchment area of the basin, then Hack's Law may be written as $A = C\ L^h$ where C is an empirical constant. The exponent "*h*" is 1.65 to 1.7 for most terrestrial rivers.

We determine Hack's Law for Saraswati Flumen, the longest channel in our study area by using the catchment area, A and stream length, L for every point along the river to derive h. Using a power law fit the exponent "*h*" is found to be 1.6. These observations might be an early indication that there could be some similarity in hydrological processes on Titan and Earth. However Hack's Law is empirical and adding more data points to it is necessary for a more accurate exponent value.

5. Discussion

Our study highlights that the large catchment area of Ontario Lacus may be the main factor for keeping Ontario filled, while nearby deeper basins in Ontario's vicinity remain dry. The catchment area extends to at least the southern mid-latitudes (40°S) based on our analysis. *Cassini* VIMS has observed clouds at southern mid-latitudes (∼40°S) (Brown et al., 2009; Rodriguez et al., 2011) in the previous flybys. Various climate models also predict the formation of clouds over these latitudes (Rannou et al., 2006; Mitchell, 2012). The presence of certain types of clouds implies precipitation in those regions. If these clouds do bring rain then our analysis suggests that a large fraction of this rain, drains into Ontario Lacus. As a consequence, the large catchment might keep Ontario Lacus filled.

The eastern sub-catchment, bound by the thin line amounts to ∼2 million km^2. Although the incomplete RADAR coverage of the eastern sub-catchment suggests some discontinuities between this catchment and Ontario Lacus, the lack of any topographic minima in the immediate vicinity gives us confidence that this sub-catchment ultimately drains towards Ontario Lacus. It should be noted, however, that even the western sub-catchment by itself represents a substantial catchment area for Ontario Lacus and therefore would still support our large catchment area hypothesis for the filled nature of this lake. The eastern sub-catchment amounts to be ∼2 million km^2. If we consider that the eastern sub-catchment does not contribute to the fluid input of Ontario Lacus we are still left with the western sub-catchment of another 2 million km^2. When multiplied by the precipitation rate (1.2 m/Titan year) the volume contribution from the western sub-catchment amounts to be 2400 km^3/ Titan year. This volume still exceeds the present volume of Ontario Lacus (1,462 km^3). The estimated values however should be treated with caution in view of the associated uncertainties.

Our mass balance model implies that the fluid input to the lake exceeds the estimated fluid loss from the lake. This, in conjunction with the huge catchment area contributing fluid is in line with our observation of currently filled Ontario Lacus at the south pole of Titan. The large catchment area of Ontario Lacus compared to the surface area of the lake would likely dwarf the fluid loss due to evaporation. We, therefore expect that even small amount of precipitation, but spread over the large catchment area of Ontario Lacus, will have the potential to keep this lake filled.

However, we acknowledge that the evaporation rate depends on the composition of the lake. If the composition of the lake is purely methane brought in by fresh rain (Turtle et al., 2011a), then it will evaporate faster because methane's vapor pressure is 3 orders of magnitude higher than ethane's. Thus, there is a probability that Ontario Lacus is highly enriched in ethane and hence ceases to evaporate any further. Since the loss tangent (or opacity) of liquid ethane is greater than that of methane (Mitchell et al., 2015), the preceding hypothesis indicates that RADAR wouldn't be able to see the depths of Ontario Lacus if it were only liquid ethane which is not the case (Mastrogiuseppe et al., 2016). Ontario Lacus probably is a mixture of ethane and methane.

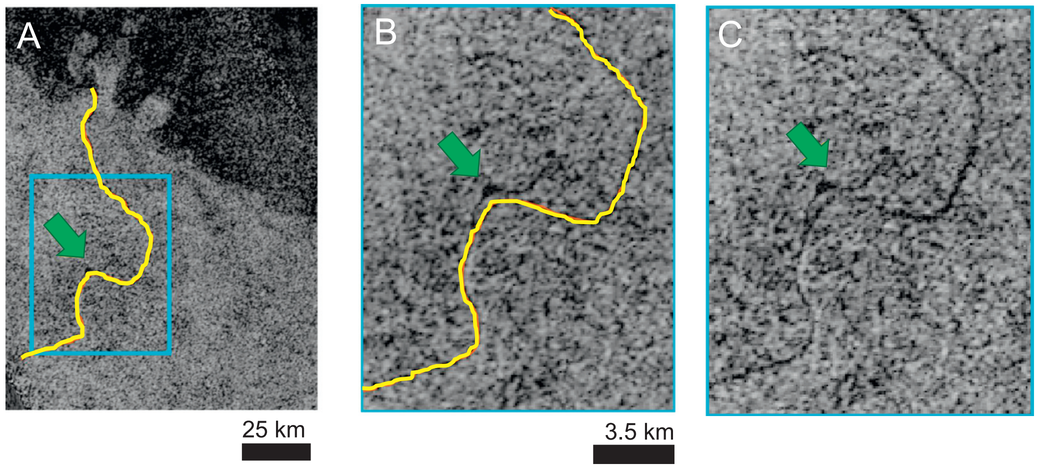

Fig. 7. T56 flyby synthetic aperture RADAR (SAR) image of Saraswati Flumen that shows a putative oxbow lake (or lakebed, perhaps). A) Shows western shoreline of Ontario Lacus in RADAR data. Saraswati Flumen's extent is shown in yellow. Saraswati Flumen is also shown in Fig. 2C by yellow arrows and the context provided in 2A and 2B. B) The blue box shows a zoomed in view of Saraswati Flumen with the green arrow pointing at the putative Oxbow lake. 7C is similar to 7B but without the stream's extent marked. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Our analysis also suggests that even though Ontario Lacus is not at the lowest elevation on the south pole, it still is in a regional minimum.

6. Conclusion

The main challenge in our study is the coarse cell size of topographical data. However, useful information can still be extracted from the available data. Better topographic coverage of the region at higher spatial resolution would significantly strengthen such analyses in the future. A hydrological model defining fluid flow combined with General Circulation Models (GCMs) to constrain the weather will likely add greater details to this study.

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References

Aharonson, O., Hayes, A.G., Lunine, J.I., Lorenz, R.D., Allison, M.D., Elachi, C., 2009. An asymmetric distribution of lakes on titan as a possible consequence of orbital forcing. Nat. Geosci. 2, 851–854. doi:10.1038/ngeo698.

Barnes, J.W., Brown, R.H., Soderblom, J.M., Soderblom, L.A., Jaumann, R., Jackson, B., Le Mouélic, S., Sotin, C., Buratti, B.J., Pitman, K.M., Baines, K.H., Clark, R.N., Nicholson, P.D., Turtle, E.P., Perry, J., 2009. Shoreline features of Titan's ontario lacus from cassini/VIMS observations. Icarus 201, 217–225. doi:10.1016/j.icarus.2008.12.028.

Barnes, J.W., Radebaugh, J., Brown, R.H., Wall, S., Soderblom, L., Lunine, J., Burr, D., Sotin, C., Le Mouélic, S., Rodriguez, S., Buratti, B.J., Clark, R., Baines, K.H., Jaumann, R., Nicholson, P.D., Kirk, R.L., Lopes, R., Lorenz, R.D., Mitchell, K., Wood, C.A., 2007. Near-infrared spectral mapping of Titan's mountains and channels. J. Geophys. Res. (Planets) 112, E11006. doi:10.1029/2007JE002932.

Brown, M.E., Smith, A.L., Chen, C., Ádámkovics, M., 2009. Discovery of fog at the south pole of titan. Astrophys. J. 706, L110–L113. doi:10.1088/0004-637X/706/1/L110.

Brown, R.H., Soderblom, L.A., Soderblom, J.M., Clark, R.N., Jaumann, R., Barnes, J.W., Sotin, C., Buratti, B., Baines, K.H., Nicholson, P.D., 2008. The identification of liquid ethane in Titan's ontario lacus. Nature 454, 607–610. doi:10.1038/nature07100.

Burr, D.M., Drummond, S.A., Cartwright, R., Black, B.A., Perron, J.T., 2013. Morphology of fluvial networks on titan: evidence for structural control. Icarus 226 (1), 742–759. http://dx.doi.org/10.1016/j.icarus.2013.06.016.

Burr, D.M., Perron, J.T., Lamb, M.P., Irwin, R.P., Collins, G.C., Howard, A.D., Sklar, L.S., Moore, J.M., Ádámkovics, M., Baker, V.R., et al., 2013. Fluvial features on titan: insights from morphology and modeling. Geol. Soc. Am. Bull. 125 (3-4), 299–321.

Cartwright, R., Clayton, J.A., Kirk, R.L., 2011. Channel morphometry, sediment transport, and implications for tectonic activity and surficial ages of titan basins. Icarus 214 (2), 561–570.

Cordier, D., Mousis, O., Lunine, J.I., Lavvas, P., Vuitton, V., 2009. An estimate of the chemical composition of Titan's lakes. Astrophys. J. 707, L128–L131. doi:10.1088/0004-637X/707/2/L128.

Cornet, T., Bourgeois, O., Le Mouélic, S., Rodriguez, S., Lopez Gonzalez, T., Sotin, C., Tobie, G., Fleurant, C., Barnes, J.W., Brown, R.H., Baines, K.H., Buratti, B.J., Clark, R.N., Nicholson, P.D., 2012a. Geomorphological significance of ontario lacus on titan: integrated interpretation of cassini VIMS, ISS and RADAR data and comparison with the etosha pan (namibia). Icarus 218, 788–806. doi:10.1016/j.icarus.2012.01.013.

Cornet, T., Bourgeois, O., Le Mouélic, S., Rodriguez, S., Sotin, C., Barnes, J.W., Brown, R.H., Baines, K.H., Buratti, B.J., Clark, R.N., Nicholson, P.D., 2012b. Edge detection applied to cassini images reveals no measurable displacement of ontario Lacus' margin between 2005 and 2010. J. Geophys. Res. (Planets) 117, 7005. doi:10.1029/2012JE004073.

Davis, W.M., 1899. The geographical cycle. Geogr. J. 14 (5), 481–504.

Elachi, C., Allison, M.D., Borgarelli, L., Encrenaz, P., Im, E., Janssen, M.A., Johnson, W.T.K., Kirk, R.L., Lorenz, R.D., Lunine, J.I., Muhleman, D.O., Ostro, S.J., Picardi, G., Posa, F., Rapley, C.G., Roth, L.E., Seu, R., Soderblom, L.A., Vetrella, S., Wall, S.D., Wood, C.A., Zebker, H.A., 2004. Radar: the Cassini titan radar mapper. Space Sci. Rev. 115, 71–110. doi:10.1007/s11214-004-1438-9.

Elachi, C., Wall, S., Janssen, M., Stofan, E., Lopes, R., Kirk, R., Lorenz, R., Lunine, J., Paganelli, F., Soderblom, L., Wood, C., Wye, L., Zebker, H., Anderson, Y., Ostro, S., Allison, M., Boehmer, R., Callahan, P., Encrenaz, P., Flamini, E., Francescetti, G., Gim, Y., Hamilton, G., Hensley, S., Johnson, W., Kelleher, K., Muhleman, D., Picardi, G., Posa, F., Roth, L., Seu, R., Shaffer, S., Stiles, B., Vetrella, S., West, R., 2006. Titan radar mapper observations from Cassini's T3 fly-by. Nature 441, 709–713. doi:10.1038/nature04786.

Fulchignoni, M., Ferri, F., Angrilli, F., Ball, A.J., Bar-Nun, A., Barucci, M.A., Bettanini, C., Bianchini, G., Borucki, W., Colombatti, G., Coradini, M., Coustenis, A., Debei, S., Falkner, P., Fanti, G., Flamini, E., Gaborit, V., Grard, R., Hamelin, M., Harri, A.M., Hathi, B., Jernej, I., Leese, M.R., Lehto, A., Lion Stoppato, P.F., López-Moreno, J.J., Mäkinen, T., McDonnell, J.A.M., McKay, C.P., Molina-Cuberos, G., Neubauer, F.M., Pirronello, V., Rodrigo, R., Saggin, B., Schwingenschuh, K., Seiff, A., Simões, F., Svedhem, H., Tokano, T., Towner, M.C., Trautner, R., Withers, P., Zarnecki, J.C., 2005. In situ measurements of the physical characteristics of Titan's environment. Nature 438, 785–791. doi:10.1038/nature04314.

Hayes, A., Aharonson, O., Callahan, P., Elachi, C., Gim, Y., Kirk, R., Lewis, K., Lopes, R., Lorenz, R., Lunine, J., Mitchell, K., Mitri, G., Stofan, E., Wall, S., 2008. Hydrocarbon lakes on Titan: distribution and interaction with a porous regolith. Geophys. Res. Lett. 35, L9204. doi:10.1029/2008GL033409.

Hayes, A.G., Wolf, A.S., Aharonson, O., Zebker, H., Lorenz, R., Kirk, R.L., Paillou, P., Lunine, J., Wye, L., Callahan, P., Wall, S., Elachi, C., 2010. Bathymetry and absorptivity of Titan's ontario lacus. J. Geophys. Res. (Planets) 115, E09009. doi:10.1029/2009JE003557.

Jaumann, R., Brown, R.H., Stephan, K., Barnes, J.W., Soderblom, L.A., Sotin, C., Le Mouélic, S., Clark, R.N., Soderblom, J., Buratti, B.J., Wagner, R., McCord, T.B., Rodriguez, S., Baines, K.H., Cruikshank, D.P., Nicholson, P.D., Griffith, C.A., Langhans, M., Lorenz, R.D., 2008. Fluvial erosion and post-erosional processes on titan. Icarus 197, 526–538. doi:10.1016/j.icarus.2008.06.002.

Kirk, R., Howington-Kraus, E., 2008. Radargrammetry on three planets. Int. Arch. Photogramm., Remote Sensing Spatial Inf. Sci. 37 (B4), 973–980.

Le Gall, A., Malaska, M.J., Lorenz, R.D., Janssen, M.A., Tokano, T., Hayes, A.G., Mastrogiuseppe, M., Lunine, J.I., Veyssière, G., Encrenaz, P., Karatekin, O., 2016. Composition, seasonal change, and bathymetry of ligeia mare, titan, derived from its microwave thermal emission. J. Geophys. Res. (Planets) 121, 233–251. doi:10.1002/2015JE004920.

Leberl, F.W., Thomas, J.K., Maurice, K.E., 1992. Initial results from the magellan stereo experiment. J. Geophys. Res. 97 (E8), 13675–13689. doi:10.1029/92JE00885.

Lora, J.M., Mitchell, J.L., 2015. Titan'S asymmetric lake distribution mediated by methane transport due to atmospheric eddies. Geophys. Res. Lett. 42, 6213–6220. doi:10.1002/2015GL064912.

Lorenz, R.D., 2014. The flushing of ligeia: composition variations across Titan's seas in a simple hydrological model. Geophys. Res. Lett. 41, 5764–5770. doi:10.1002/2014GL061133.

Lorenz, R.D., Stiles, B.W., Aharonson, O., Lucas, A., Hayes, A.G., Kirk, R.L., Zebker, H.A., Turtle, E.P., Neish, C.D., Stofan, E.R., Barnes, J.W., 2013. A global topographic map of titan. Icarus 225, 367–377. doi:10.1016/j.icarus.2013.04.002.

MacKenzie, S.M., Barnes, J.W., 2016. Compositional similarities and distinctions between titans evaporitic terrains. Astrophys. J. 821, 17. doi:10.3847/0004-637X/821/1/17.

MacKenzie, S.M., Barnes, J.W., Sotin, C., Soderblom, J.M., Mouélic, S.L., Rodriguez, S., Baines, K.H., Buratti, B.J., Clark, R.N., Nicholson, P.D., McCord, T.B., 2014. Evidence of titan's climate history from evaporite distribution. Icarus 243 (0), 191–207. http://dx.doi.org/10.1016/j.icarus.2014.08.022.

Mastrogiuseppe, M., Hayes, A., Poggiali, V., Lunine, J., Seu, R., Hofgartner, J., Le Gall, A., Lorenz, R., 2016. Bathymetry and composition of Titan's hydrocarbon seas from the Cassini RADAR altimeter. In: EGU General Assembly Conference Abstracts. In: EGU General Assembly Conference Abstracts, vol. 18, p. 13172.

Mastrogiuseppe, M., Poggiali, V., Hayes, A., Lorenz, R., Lunine, J., Picardi, G., Seu, R., Flamini, E., Mitri, G., Notarnicola, C., Paillou, P., Zebker, H., 2014. The bathymetry of a titan sea. Geophys. Res. Lett. 41, 1432–1437. doi:10.1002/2013GL058618.

Miller, S., Walker, A., 1993. Further developments of leica digital photogrammetric systems by helava. ACSM ASPRS Annual Convention, 3. American Soc Photogrammetry & Remote Sensing+ Amer Cong On. 256–256.

Miller, S., Walker, A., 1995. Die entwicklung der digitalen photogrammetrischen systeme von leica und helava. Z. Photogramm. Fernerkundung 63 (1), 4–16.

Mitchell, J.L., 2012. Titan's transport-driven methane cycle. Astrophys. J. 756, L26. doi:10.1088/2041-8205/756/2/L26.

Mitchell, K.L., Barmatz, M.B., Jamieson, C.S., Lorenz, R.D., Lunine, J.I., 2015. Laboratory measurements of cryogenic liquid alkane microwave absorptivity and implications for the composition of ligeia mare, titan. Geophys. Res. Lett. 42, 1340–1345. doi:10.1002/2014GL059475.

Mitri, G., Showman, A.P., Lunine, J.I., Lorenz, R.D., 2007. Hydrocarbon lakes on Titan. Icarus 186, 385–394. doi:10.1016/j.icarus.2006.09.004.

Perron, J.T., Lamb, M.P., Koven, C.D., Fung, I.Y., Yager, E., Ádámkovics, M., 2006. Valley formation and methane precipitation rates on titan. J. Geophys. Res. (Planets) 111, 11001. doi:10.1029/2005JE002602.

Porco, C.C., Baker, E., Barbara, J., Beurle, K., Brahic, A., Burns, J.A., Charnoz, S., Cooper, N., Dawson, D.D., Del Genio, A.D., Denk, T., Dones, L., Dyudina, U., Evans, M.W., Fussner, S., Giese, B., Grazier, K., Helfenstein, P., Ingersoll, A.P., Jacobson, R.A., Johnson, T.V., McEwen, A., Murray, C.D., Neukum, G., Owen, W.M., Perry, J., Roatsch, T., Spitale, J., Squyres, S., Thomas, P., Tiscareno, M., Turtle, E.P., Vasavada, A.R., Veverka, J., Wagner, R., West, R., 2005. Imaging of titan from the cassini spacecraft. Nature 434, 159–168.

Rannou, P., Montmessin, F., Hourdin, F., Lebonnois, S., 2006. The latitudinal distribution of clouds on titan. Science 311, 201–205. doi:10.1126/science.1118424.

Rodriguez, S., Le Mouélic, S., Rannou, P., Sotin, C., Brown, R.H., Barnes, J.W., Griffith, C.A., Burgalat, J., Baines, K.H., Buratti, B.J., Clark, R.N., Nicholson, P.D., 2011. Titan'S cloud seasonal activity from winter to spring with cassini/VIMS. Icarus 216, 89–110. doi:10.1016/j.icarus.2011.07.031.

Schneider, T., Graves, S.D.B., Schaller, E.L., Brown, M.E., 2012. Polar methane accumulation and rainstorms on titan from simulations of the methane cycle. Nature 481, 58–61. doi:10.1038/nature10666.

Sotin, C., Lawrence, K.J., Reinhardt, B., Barnes, J.W., Brown, R.H., Hayes, A.G., Le Mouélic, S., Rodriguez, S., Soderblom, J.M., Soderblom, L.A., Baines, K.H., Buratti, B.J., Clark, R.N., Jaumann, R., Nicholson, P.D., Stephan, K., 2012. Observations of Titan's northern lakes at 5 μm: implications for the organic cycle and geology. Icarus 221, 768–786. doi:10.1016/j.icarus.2012.08.017.

Stiles, B.W., Hensley, S., Gim, Y., Bates, D.M., Kirk, R.L., Hayes, A., Radebaugh, J., Lorenz, R.D., Mitchell, K.L., Callahan, P.S., et al., 2009. Determining titan surface topography from cassini sar data. Icarus 202 (2), 584–598.

Stofan, E.R., Elachi, C., Lunine, J.I., Lorenz, R.D., Stiles, B., Mitchell, K.L., Ostro, S., Soderblom, L., Wood, C., Zebker, H., Wall, S., Janssen, M., Kirk, R., Lopes, R., Paganelli, F., Radebaugh, J., Wye, L., Anderson, Y., Allison, M., Boehmer, R., Callahan, P., Encrenaz, P., Flamini, E., Francescetti, G., Gim, Y., Hamilton, G., Hensley, S., Johnson, W.T.K., Kelleher, K., Muhleman, D., Paillou, P., Picardi, G., Posa, F., Roth, L., Seu, R., Shaffer, S., Vetrella, S., West, R., 2007. The lakes of titan. Nature 445, 61–64. doi:10.1038/nature05438.

Tarboton, D.G., 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. Water Resour. Res. 33 (2), 309–319. doi:10.1029/96WR03137.

Turtle, E.P., Del Genio, A.D., Barbara, J.M., Perry, J.E., Schaller, E.L., McEwen, A.S., West, R.A., Ray, T.L., 2011. Seasonal changes in Titan's meteorology. Geophys. Res. Lett. 38, 3203. doi:10.1029/2010GL046266.

Turtle, E.P., Perry, J.E., Hayes, A.G., McEwen, A.S., 2011. Shoreline retreat at Titan's ontario lacus and arrakis planitia from cassini imaging science subsystem observations. Icarus 212, 957–959. doi:10.1016/j.icarus.2011.02.005.

Turtle, E.P., Perry, J.E., McEwen, A.S., Del Genio, A.D., Barbara, J., West, R.A., Dawson, D.D., Porco, C.C., 2009. Cassini imaging of Titan's high-latitude lakes, clouds, and south-polar surface changes. Geophys. Res. Lett. 36, L2204. doi:10.1029/2008GL036186.

Wall, S., Hayes, A., Bristow, C., Lorenz, R., Stofan, E., Lunine, J., Le Gall, A., Janssen, M., Lopes, R., Wye, L., Soderblom, L., Paillou, P., Aharonson, O., Zebker, H., Farr, T., Mitri, G., Kirk, R., Mitchell, K., Notarnicola, C., Casarano, D., Ventura, B., 2010. Active shoreline of ontario lacus, titan: a morphological study of the lake and its surroundings. Geophys. Res. Lett. 37, L5202. doi:10.1029/2009GL041821.

Willemin, J.H., 2000. Hack'S law: sinuosity, convexity, elongation. Water Resour. Res. 36, 3365–3374. doi:10.1029/2000WR900229.

Wobus, C., Whipple, K.X., Kirby, E., Snyder, N., Johnson, J., Spyropolou, K., Crosby, B., Sheehan, D., 2006. Tectonics from topography: procedures, promise, and pitfalls. Geol. Soc. Am. Spec. Papers 398, 55–74.

Wood, C.A., Stofan, E.R., Hayes, A.G., Kirk, R.K., Lunine, J.I., Radebaugh, J., Malaska, M., 2013. Morphological evidence for former seas near Titan's south pole. In: Lunar and Planetary Science Conference. In: Lunar and Planetary Inst. Technical Report, 44, p. 1764.

Wye, L.C., Zebker, H.A., Lorenz, R.D., 2009. Smoothness of Titan's ontario lacus: constraints from cassini RADAR specular reflection data. Geophys. Res. Lett. 36, L16201. doi:10.1029/2009GL039588.