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The influence of subsurface flow on lake formation and north polar lake distribution on Titan

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ABSTRACT

Observations of lakes, fluvial dissection of the surface, rapid variations in cloud cover, and lake shoreline changes indicate that Saturn's moon Titan is hydrologically active, with a hydrocarbon-based hydrological cycle dominated by liquid methane. Here we use a numerical model to investigate the Titan hydrological cycle – including surface, subsurface, and atmospheric components – in order to investigate the underlying causes of the observed distribution and sizes of lakes in the north polar region. The hydrocarbon-based hydrological cycle is modeled using a numerical subsurface flow model and analytical runoff scheme, driven by a general circulation model with an active methane-cycle. This model is run on synthetically generated topography that matches the fractal character of the observed topography, without explicit representation of the effects of erosion and deposition. At the scale of individual basins, intermediate to high permeability (10^{-8}–10^{-6} cm^2) aquifers are required to reproduce the observed large stable lakes. However, at the scale of the entire north polar lake district, a high permeability aquifer results in the rapid flushing of methane through the aquifer from high polar latitudes to dry lower polar latitudes, where methane is removed by evaporation, preventing large lakes from forming. In contrast, an intermediate permeability aquifer slows the subsurface flow from high polar latitudes, allowing greater lake areas. The observed distribution of lakes is best matched by either a uniform intermediate permeability aquifer, or a combination of a high permeability cap at high latitudes surrounded by an intermediate permeability aquifer at lower latitudes, as could arise due to karstic processes at the north pole. The stability of Kraken Mare further requires reduction of the evaporation rate over the sea to 1% of the value predicted by the general circulation model, likely as a result of dissolved ethane, nitrogen, or organic solutes, and/or a climatic lake effect. These results reveal that subsurface flow through aquifers plays an important role in Titan's hydrological cycle, and exerts a strong influence over the distribution, size, and volatile budgets of Titan's lakes.

1. Introduction

The surface of Saturn's largest moon Titan has been extensively modified by processes related to liquid hydrocarbons on the surface. Similar to water on Earth, methane at Titan's surface is near its vapor point and exists in both the gas and liquid phases, suggesting that it is the primary constituent in the hydrocarbon-based hydrological cycle. Ponded liquid on Titan's surface is primarily concentrated around the north polar region (Stofan et al., 2007) in lakes with variable morphology (Hayes et al., 2008). Lakes with steep-sided and smooth shorelines with no observable fluvial source may be indicative of karst or seepage morphology (Mitchell et al., 2008; Cornet et al. 2015) and can be either liquid filled or empty (Hayes et al., 2008). Larger lakes and seas with irregular shorelines, appear to be located in topographic lows (Stiles et al., 2009) at the terminus of fluvial features (Cartwright et al., 2011; Langhans et al., 2012). Surface modification by fluvial dissection (Burr et al., 2006; Perron et al., 2006; Jaumann et al., 2008; Lorenz et al., 2008a; Burr et al., 2009; Black et al., 2012; Langhans et al., 2012) is driven by precipitation reaching Titan's surface (Tokano et al., 2001).

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The current orbital obliquity of the Saturn system of 26.7° causes seasonal variations in solar insolation (Lorenz et al., 1999; Stiles et al., 2009), which in turn drives seasonal variations in the polar precipitation and evaporation rates with an annual period of 29.5 years (note that the unit of time "year" will refer to an Earth-year throughout this work, unless specified as a Titan-year). During northern summer, high solar insolation results in atmospheric upwelling at the north polar region, causing rapid cooling of air parcels and condensation of methane to form clouds and precipitation. Observational evidence of cloud formation (Porco et al., 2005) and subsequent darkening of the surface in the south polar region during southern summer (Schaller et al., 2006; Turtle et al., 2011) suggest that convective storm systems bring precipitation to the surface. General circulation models (GCMs) predict increases in the evaporation and precipitation rates (Tokano et al., 2001; Mitchell et al., 2006; Schneider et al., 2012; Lora et al., 2014; Newman, 2015) due to high solar insolation at the polar regions during the summer and spring seasons.

Temporal changes, thought to be due to changes in the distribution of methane on the surface, have been observed at the south polar region and the tropics on Titan. Changes in the surface albedo in the south polar region and tropics are thought to be due to precipitation events and subsequent evaporation (Turtle et al., 2009 , 2011). Evidence for temporal changes in the distribution of lakes includes possible present-day changes in the location of the shoreline of Ontario Lacus in the south polar region (Turtle et al., 2011), and dry lakebed morphologies in the north polar region (Hayes et al., 2008) suggesting long-term changes in lake stability. The proposed shoreline change at Ontario Lacus suggests an average loss rate of ~1 m/yr for lakes in the south polar region based on an average shoreline recession of ~2 km (Hayes et al., 2011). However, alternative interpretations have suggested that the spatial resolution of the instrument used was inadequate for determining any measurable shoreline recession (Cornet et al., 2012). While dry lakebed morphologies (Hayes et al., 2008), inferred long-term lake level changes (Stofan et al., 2007; Lucas et al., 2014) indicate long-term changes in lakes, and transient lake features have been observed between subsequent Cassini flybys (Hofgartner et al., 2014), shoreline change in filled northern lakes during the Cassini mission has yet to be observed (Hayes et al. 2011). Based on predicted evaporation and precipitation rates, Mitri et al. (2007) placed theoretical upper limits on lake recession, predicting up to 30 km/yr for shoreline slopes of 0.1% based on altimetric profiles (Elachi et al., 2005). However, that early study required several simplifying assumptions, including constant slope, constant wind speed, and a lack of methane supplied from the surrounding watershed. Hayes et al. (2008) modeled temporal changes in lake area for lakes perched above an aquifer and separated from it by an unsaturated zone, specifically focusing on the timescales for lake disappearance and the influence of aquifer permeability on subsurface and atmospheric exchange of liquid methane. They found that for permeabilities less than 10^{-6} cm^2, lake recession becomes limited by the evaporation rate and occurs on the order of seasonal timescales. Higher permeabilities, on the order of 10^{-6} cm^2 to 10^{-5} cm^2, were found to be more consistent with seepage morphology lakes at the north polar region based on the size of these lakes.

Thus, previous work has revealed evidence for atmosphere-surface exchange of volatiles, transport of liquid over the surface, the existence of stable lakes and seas, and possible limited temporal changes in lakes and seas on Titan. Although there is clear evidence for an active hydrological cycle, significant work remains to be done to understand the nature of that hydrological cycle. In particular, the role of subsurface flow in unconfined aquifers, the influence of this flow on the stability and distribution of lakes, and the properties of Titan aquifers are poorly understood. Subsurface hydrology on regional and global scales on Earth and Mars are important for understanding the distribution and activity of groundwater. A lack of ground truth observations of Titan's subsurface hydrological properties necessitates comparison of hydrologic models with the observed distribution and behavior of lakes on Titan. While similar in many respects to the water-based hydrological cycles on Earth and Mars, Titan's hydrocarbon-based hydrological cycle involves a fluid with a lower viscosity and density (depending on the assumed fluid composition), that flows under the influence of a weaker gravitational acceleration on a surface with lower relief, and driven by a longer seasonal cycle. These differences highlight the importance of theoretical studies of Titan's hydrological cycle.

In this study, we model the full methane-based hydrological cycle of Titan, including atmospheric, surface, and subsurface components. In order to investigate lake behavior on both basin and polar scales, we combined a numerical subsurface hydrology model with an analytical surface runoff model, driven by the outputs from a general circulation model. We compare the results to observations of the distribution and sizes of lakes in order to constrain subsurface properties. In Section 2, the Titan hydrological model is described in detail. In Section 3 we use basin-scale hydrological models driven by precipitation and evaporation rates from a general circulation model at individual latitudes to investigate the behavior of hydrology on Titan at the scale of individual basins. The basin-scale model is then expanded to a polar model extending from the pole to mid-latitudes in Section 4, with latitudinally varying precipitation and evaporation rates. These polar models allow us to investigate the influence of different hydrological parameters on the formation of large seas and the distribution of lakes at the north polar region. The results are compared with observational constraints in the form of the observed lake distribution at the north polar region, and implications for Titan hydrology are discussed.

2. Methods: modeling hydrology on Titan

In order to investigate lake behavior on both basin and polar scales, we developed a numerical model that incorporates the atmospheric, surface, and subsurface components of Titan's hydrological cycle. The model was run on two-dimensional grids representing the surface topography of either an individual basin or the entire north polar region (Section 2.1). The amount of methane that either recharges the aquifer or channelizes as surface runoff was determined from the outputs of a general circulation model (Section 2.2) using an Earth-based scaling relationship dependent on the precipitation and evaporation potential (defined as the evaporation rate that would occur from a standing body of liquid methane) (Section 2.3). The subsurface flow was modeled using a finite-difference approximation to the groundwater flow equation with parameters appropriate for Titan (Section 2.4). Surface runoff was modeled using a linear reservoir model with parameters appropriate for terrestrial basins (Section 2.5). The model allowed lakes to form and evolve naturally as a result of the balance between the surface, subsurface, and atmospheric fluxes of methane (Section 2.6).

2.1. Topography

Both the gravitationally driven flow of fluids in the subsurface and the surface runoff are dominated by the effects of the surface topography. For this study, we use topography derived from the overlapping antenna beams of the Cassini synthetic aperture radar (SAR) for all Titan flybys up through the T84 flyby (Stiles et al., 2009). The total relief (referenced to the geoid) on Titan is ~2.5 km, while the relief on smaller scales relevant to the basin-scale hydrological modeling in this study is ~1.4 km (Fig. 1). In an