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Dynamical modelling of river deltas on Titan and Earth

Piotr P. Witek*, Leszek Czechowski

Institute of Geophysics, Faculty of Physics, University of Warsaw, ul. Pasteura 7, 02-093 Warszawa, Poland

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ABSTRACT

The surface of Titan hosts a unique Earth-like environment with lakes and rivers, and active 'hydrologic' cycle of methane. We investigate sediment transport in Titanian rivers and deposition in Titanian lakes with particular attention to formation of river deltas. The obtained results are compared with analogous terrestrial processes. The numerical model based on Navier–Stokes equations for depth-integrated two dimensional turbulent flow and additional equations for bed-load and suspended-load sediment transport was used in our research. It is found that transport of icy grains in Titanian rivers is more effective than silicate grains of the same size in terrestrial rivers for the same assumed total discharge. This effect is explained theoretically using dimensionless form of equations or comparing forces acting on the grains. Our calculations confirm previous results (Burr et al., 2006. Icarus. 181, 235–242). We calculate also models with organic sediments of different densities, namely 1500 and 800 kg m^{-3}. We found substantial differences between materials of varying densities on Titan, but they are less pronounced than differences between Titan and Earth.

1. Introduction

Titan and Earth are the only celestial bodies in the Solar System where current p–T conditions allow for permanent presence of the liquid on their surfaces as well as for hydrologic/hydrocarbon cycles. The precipitation is observed on both bodies as well as the river and stream valleys formed by surface runoff. The processes in these rivers are the subject of investigation of ExRiMoG group (Extraterrstrial Rivers' Modeling Group). In the present paper we consider the evolution of deltas on Titan and Earth. We use numerical model based on the physical equations of fluid dynamics. Such models are widely used for terrestrial rivers but according to our best knowledge it is the first paper where dynamical numerical model is used for modelling of Titan's deltas. The scope of the research is limited to flow with moderate discharge. It is an extension of research presented by Witek and Czechowski (2013).

Terrestrial deltas are the subject of numerous papers and textbooks; e.g. Edmonds and Slingerland (2007), Julien (2010), Melosh (2011), Robert (2003). Some of their results are presented in the present section. The papers that concern extraterrestrial deltas are discussed in Section 4.5.

The paper is organized as follows. In the rest of Introduction we present basic data concerning Titan, its rivers and lakes, as well as, the basic classification of rivers' deltas. Section 2 presents equations, boundary conditions and parameters of our model. The results are given in Section 3. Section 4 contains discussion of our results, their comparison with some other research, explanations of some observed processes and short discussion concerning possible dimensionless system of equations. Conclusions are in the last section.

1.1. Surface of Titan

Titan's low density (1880 kg m^{-3}) is typical for icy moons and indicates a large fraction of water ice in composition of the satellite. Titan is large enough to be internally differentiated, with an external shell thought to be composed mostly of the low-pressure form of water ice (ice I). The surface is covered by a thin layer of unknown materials, most likely a mixture of precipitated organic materials derived from atmospheric photochemistry and crystalline ice (Sotin et al., 2009). The number of impact craters observed on Titan is very low (around 60, according to Neish and Lorenz, 2014), suggesting a high rate of resurfacing (Jaumann et al., 2009). The data concerning topography are sparse; the maximum known altitude difference is only about 2.5 km on the scale of the whole moon (Lorenz et al., 2013).

Lakes of liquid hydrocarbons and numerous landforms created by fluvial activity have been observed by the *Cassini-Huygens* mission on the surface of Titan (Stofan et al., 2007; Langhans et al., 2012). Channels thought to be river valleys are present on the surface; some of them form dendritic networks. Some channels are radar-dark so they could be presently filled with liquid. Other channels are radar-bright, indicating a rough, dry surface, most probably grains of solid material (Lorenz et al., 2008). Several dry valleys have alluvial fans at the terminus. Many dark channels

* Corresponding author. Tel.: +48 509849765.
E-mail address: ppwit@igf.fuw.edu.pl (P.P. Witek).

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terminate in lakes, especially in the polar regions of Titan where large clusters of lakes exist.

It is observed that appearance and disappearance of clouds in the atmosphere is associated with changes in brightness of the surface (Turtle et al., 2011a). This indicates the presence of active volatile cycle analogous to terrestrial hydrologic cycle (Lunine and Lorenz, 2009).

1.2. Hydrocarbon cycle

The atmosphere of Titan consists mostly of molecular nitrogen (95% in the troposphere) with addition of methane and noble gases. Various organic compounds are synthesized from methane and nitrogen by set of complex photochemical reactions in the upper atmosphere (Lavvas et al., 2008). Under Titanian conditions, methane is able to form clouds and rains down to the surface. The rains have a seasonal character (Turtle et al., 2011a). When Titan (and Saturn) is near the solstice the rains occur in the summer hemisphere, and closer to equinox the rains may fall in the tropics (Lunine and Lorenz, 2009). In general, transport of methane from the atmosphere to the surface could take form of the steady drizzle and average precipitation rates are comparable to terrestrial arid and semi-arid regions (Tokano et al., 2006). The precipitation could also have form of sudden massive storm events. The resulting flash floods could cause large-scale changes in the appearance of the surface (Turtle et al., 2011a). Note that the most dramatic changes of terrestrial rivers occur during high discharge period (e.g. floods). Bankfull discharge is dominant for alluvial channels (e.g. Julien, 2002). Therefore, one can expect that the flash floods are likely also the dominant driver of large scale processes on Titan. Such events are however known to be relatively infrequent. We plan to calculate the effects these processes in the next papers but first we investigate the evolution for typical discharge. Therefore, in the present research we consider moderate discharge, an order of magnitude smaller than bankfull discharge for our channel.

1.3. Titanian lakes

Numerous hydrocarbon lakes exist in the polar regions of Titan and few lakes have been postulated in the equatorial region as well (Griffith et al., 2012). Some of these features are radar-dark; they are thought to be filled with liquid and they are called ‘lakes’ (*lacus*). Other are radar-bright, which suggests that the rough lake bed is exposed. The largest cluster of lakes exists near the north pole of Titan. Three of these lakes are large enough to be classified as ‘seas’ (*maria*). Several large rivers enter the seas, terminating in estuaries.

On the southern hemisphere of Titan the largest hydrocarbon lake is Ontario Lacus, the fifth largest body of liquids identified on the moon. It is situated in 300 m deep depression with flat floor, but the thickness of the liquid layer is not expected to exceed a few meters (Lorenz et al., 2010a). The currently observed lake may be a remnant of much larger sea of the size of Ligea Mare (Stofan et al., 2012). Observations have shown the bright annulus surrounding the dark lake, probably composed of evaporites (Barnes et al., 2011). The annuli of that type develop over terrestrial lakes under the conditions of prolonged drought (Barnes et al., 2009). Observations have also shown the reduction of visible area of the lake, interpreted as the recession of the southern shoreline (Turtle et al., 2011b). If this interpretation is correct, then the evaporation rate corresponds to fall of the lake level with the rate of 1 m per year (Hayes et al., 2011). Other interpretations of this phenomenon (without assumption of the fall of the lake level) have been also proposed (Cornet et al., 2012).

Over 100 km-long river valley connects to Ontario Lacus at the south-western shore. At the mouth of the river there exists a unique lobate structure entering the lake (Fig. 2). It is interpreted as a protruding delta, the first form of this kind observed on the surface of Titan. The delta has two lobes; their positions relative to the visible river channel suggest switching of the distributary channels (Wall et al., 2010). The resolution of the images is too low to observe the feeder channels. They are supposed to flow inside the lobes. The valley is about 1 km wide, but the width of the actual river channel is unknown (Wall et al., 2010).

The tides of low amplitude are predicted in Ontario Lacus (Barnes et al., 2009; Tokano, 2010), however the apparent delta on the coast of the lake does not appear to show signs of tidal modification. The delta front may be modified by wave action, but the structure is generally dominated by the river processes (Wall et al., 2010). Therefore, in the present research we adopt the model with no tides or waves.

Observations with Visual and Infrared Mapping Spectrometer (VIMS) have revealed the presence of ethane in Ontario Lacus (Brown et al., 2008). The compostion of Titan lakes in equilibrium with the atmosphere is predicted to be ethane-rich (Cordier et al., 2009). However, the northern seas could be out of equilibrium with the atmosphere, much as on the Earth (Lorenz, 2014). Currently no river delta has been identified on the shores of northern seas. Some of the river valleys seem flooded—e.g. southern coasts of Ligeia Mare have a ria morphology (Lorenz et al., 2012). Terrain in the vicinity of this sea is hilly, southern banks have steep slopes. The floor of this *mare* can be seen by *Cassini* radar through the liquid, which is now thought to be up to 160 m deep (Mastrogiuseppe et al., 2014; Wye et al., 2010). According to General Circulation Models (GCM) the precipitation in such high latitude prevails over evaporation of methane and Ligea Mare is thought to be methane-rich. This result is consistent with the dielectric constant ($\varepsilon \sim 1.7$) suggested by interpretation of microwave radiometry data (Lorenz, 2014). Several channels appear to begin in the surrounding terrain and continue on the sea floor. These observations could indicate geologically recent rise of the liquid level: some valleys were formed when the surface of the lake was lower (Lorenz et al., 2012). Therefore, some depositional landforms created in the past may be currently drowned. The other factor responsible for the formation of channels visible on the lake floor could be turbidity currents.

1.4. Titanian rivers

Valleys with morphology suggesting fluvial origin are distributed around the whole globe of Titan. They are visible in polar areas containing lakes, but they occur also in dry equatorial regions. Areas close to the north pole of Titan are believed to be humid, based on large number of lakes, whereas equatorial regions are arid or semi-arid. In the southern hemisphere the number of lakes is much lower, suggesting climate changes possibly due to asymmetric forcing (Aharonson et al., 2009; Lunine and Lorenz, 2009). The channels can be radar-bright, indicating centimetre-scale rough terrain, probably an empty river bed covered with pebbles similar to those observed by the *Huygens* probe. The radar-dark channels may be either filled with liquid or deposits of particles of sizes smaller than the radar wavelength (2.17 cm).

It should be noted, that *Cassini* spacecraft instruments have limited resolution (~300 m for RADAR and ~500 m for VIMS (Visual and Infrared Mapping Spectrometer) and small valleys are not visible in SAR (Synthetic Aperture Radar) images. For example, the *Huygens* probe imaged a small dendritic network of channels, during its descent through the atmosphere, invisible for *Cassini* instruments (Tomasko et al., 2005; Grotzinger et al., 2013).

It should be noted that images acquired by *Cassini* show river valleys, but the actual river channel may occupy only a tiny fraction of the valley. The valleys on the Earth are well known to