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Impact of seas/lakes on polar meteorology of Titan: Simulation by a coupled GCM-Sea model

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ABSTRACT

The detection of large hydrocarbon seas/lakes near the poles by the Cassini spacecraft raises the question as to whether and how polar seas affect the meteorology on Titan. The polar meteorology and methane hydrological cycle in the presence of seas are investigated by a three-dimensional atmospheric general circulation model coupled to a one-dimensional sea energy balance model considering the observed sea/lake geography. The sea composition has a large control on the seasonal evolution of seas, temperature and wind system in the polar region, particularly in the north where large seas are located. The surface of ethane-rich seas, which do not evaporate methane, undergo a large seasonal temperature variation and the sea surface is often warmer than the surrounding land surface. Land breeze in summer towards the seas causes a moisture convergence over the seas, which leads to enhanced summer precipitation in the sea area. On the other hand, methane-rich seas evaporate some methane and are therefore colder than the surroundings. This causes a sea breeze across the north pole in summer, which blows away the moisture from the polar region, so precipitation becomes scarce in the north polar region. The breeze can become stronger than the tidal wind. Sea evaporation peaks in winter, when the temperature and average methane mixing ratio in the planetary boundary layer become lowest. The sea level predominantly rises in summer by precipitation and retreats in winter by evaporation. The meteorology in the south polar region is less sensitive to the composition of the lakes because of the paucity and smallness of southern lakes. Lake-effect precipitation can occur either by moisture convergence by the breeze or humidity enhancement over the seas, but is more characteristic of warm seasons than of cold seasons.

1. Introduction

Saturn's moon Titan has long been suggested to have a global-scale ocean of hydrocarbons on the surface (Lunine et al., 1983; Flasar, 1983). This naturally led to the expectation that an Earth-like hydrological cycle based on hydrocarbons may exist on Titan (e.g., Lunine and Atreya, 2008). The presence of a global ocean on Titan has eventually been discarded (West et al., 2005; Porco et al., 2005). On the other hand, extended seas/lakes of hydrocarbons have been detected by the Cassini Radar in the north polar region (Stofan et al., 2007). As of May 2007, 2.4% of those parts of Titan's surface already mapped by the radar was found to be covered by lakes (Hayes et al., 2008; Lorenz et al., 2008a). Visual images acquired in 2008 revealed the further southward extension of Kraken Mare, the largest sea on Titan (Brown et al., 2009; Turtle et al., 2009). Furthermore, clear spectroscopic evidence for liquid ethane was found in Ontario Lacus, one of the southern lakes, by the Cassini VIMS (Visual Infrared Mapping Spectrometer) (Brown et al., 2008). If these seas indeed contain liquid hydrocarbons, the evaporation from these seas may affect the methane hydrological cycle. The long-term interaction between the atmosphere and the putative hydrocarbon ocean has been investigated for many years by theoretical models (e.g. Lunine et al., 1983; McKay et al., 1993). However, these studies were concerned with the coupled evolution of the atmosphere and oceans (or seas) on geological timescales rather than with the hydrological cycle on seasonal timescales.

Mitri et al. (2007) were the first who addressed the possible influence of hydrocarbon seas/lakes on the atmosphere from a theoretical point of view. They calculated the methane evaporation rate from such lakes for different lake compositions and lake surface temperatures and concluded that the lake evaporation could readily provide the present total methane abundance in Titan's atmosphere. A scenario Stofan et al. (2007) proposed is one in which the lakes grow in winter by precipitation and shrink or even dry up by evaporation in summer. Furthermore Mitri et al. (2007) suggested that the mid-latitude and equatorial region may experience a progressive growth in methane humidity as a result of lake evaporation.

Hayes et al. (2008), on the other hand, noticed that as of May 2007 none of the multiply observed lakes so far has displayed

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any shoreline change. Therefore, they suggested that a methane table exists, which keeps the lake level constant. Their analytical model indicated that the timescale for flow into and out of lakes assuming flow through porous media is comparable to the seasonal cycles. Therefore, lake evaporation may be balanced by vertical seepage rather than by precipitation. Griffith et al. (2008) argued that the solar energy the polar region receives is insufficient to substantially humidify the northern hemisphere by lake evaporation. However, they estimated that the humidity north of 60° latitude would rise by 15% due to lake evaporation and some of the small shallow lakes may dry up in summer. Observations of the south polar region indicate the likelihood of some lake level change, though. Barnes et al. (2009) found evidence of shoreline change over time in Ontario Lacus although the timescale, cause and amplitude of the lake level change remain uncertain.

Meanwhile, there are observations that seem to support a possible link between the presence of hydrocarbon seas/lakes and meteorology. Using ground-based telescopes and imaging instruments onboard Cassini, Brown et al. (2009) discovered clouds in the cold late-winter north polar region, which appear confined to the same latitudes as those of the largest known seas. They proposed that they are Titan's analogues for lake-effect clouds and that they may have been convectively caused by temperature differences between the lakes and atmosphere. Turtle et al. (2009) found a darkening of Ontario Lacus that they ascribe to ponding of the lake by precipitation from recent rainstorms in that region.

The present work mainly addresses the question as to how the presence of polar seas affect the atmospheric hydrological cycle and polar meteorology and in turn how the seas are affected by the atmosphere. Particularly, it tests the various recent hypotheses on the relationship between lakes and clouds/precipitation (Stofan et al., 2007; Mitri et al., 2007; Lunine and Atreya, 2008; Brown et al., 2009; Turtle et al., 2009) in the framework of a global model. For this purpose a three-dimensional general circulation model (GCM) coupled to a sea thermodynamics model is used taking into account the geographical distribution of the observed seas. Throughout this paper large hydrocarbon deposits on the surface are referred to as "seas" in most cases, but they are regarded as synonyms for the term "lakes" that is also being used in the literature.

2. Model description

2.1. Model outline

The simulation is carried out with a three-dimensional atmospheric GCM that is coupled to a one-dimensional sea energy balance (thermal stratification) model. The atmosphere–sea coupling is interactive and follows a similar approach in terrestrial climate models (e.g. Hostetler et al., 1993).

The atmospheric part of the methane hydrology model is based on the GCM of Tokano et al. (2001) which simulated the global methane transport and large-scale methane condensation. The model solves a set of primitive equations (with hydrostatic approximation) on grid points to predict the temporal evolution of the global wind, pressure, temperature and methane mixing ratio. The model domain consists of 32 longitudinal, 24 latitudinal and 60 vertical gridpoints. Gaseous methane is treated as a passive - tracer, and is subject to global transport as well as condensation, precipitation and evaporation. Clouds and precipitation (hydrometeors) are not treated as separate prognostic quantities, but are diagnosed from the change in the methane relative humidity. Only large-scale condensation (stratiform condensation) is taken into account, i.e. subgrid-scale moist convection is not treated. Details on the methane hydrology are explained in Section 2.2. The radiation scheme is that of McKay et al. (1989), which was recently found to nicely reproduce the vertical profile of radiative heating and cooling rate measured by Huygens (Tomasko et al., 2008). The GCM of Tokano et al. (2001) has since been updated and now includes Saturn's gravitational tide (Tokano and Neubauer, 2002), prediction of the surface temperature (Tokano, 2005) and atmospheric structure profile measured by Huygens (Fulchignoni et al., 2005).

The GCM is coupled to a one-dimensional sea energy balance model (Tokano, 2009), which is applied only to those grid points that are aimed to represent the seas. The sea model described in Section 2.3 calculates the surface energy balance to predict the surface temperature, sea interior temperature, methane evaporation rate and the sea level change by evaporation and precipitation. The evaporation depends on the equilibrium between the partial pressure in the atmosphere and seas via Raoult's law and Henry's law.

2.2. Treatment of atmospheric methane hydrology

2.2.1. Methane condensation

In Tokano et al. (2001) large-scale methane condensation was assumed to occur either if the relative humidity with respect to liquid CH_4—N_2 binary mixture exceeds 100% or 150%. In situ humidity measurements near the equator by the Huygens probe, however, have shown that large supersaturation did not exist at the entry site (Tokano et al., 2006). The methane mixing ratio almost exactly followed the saturation curve with respect to liquid CH_4—N_2 below 16 km (freezing level of this mixture) and with respect to solid CH_4 at higher altitudes. This is also consistent with laboratory experiments by Curtis et al. (2008) according to which methane nucleation begins at a relative humidity only slightly above unity by virtue of methane adsorption to tholins.

The model assumes that stratiform condensation begins whenever the relative humidity exceeds 100%, ruling out any supersaturation. Latent heat is exchanged in case of condensation and evaporation of falling rain. This scenario corresponds to that measured by Huygens (Tokano et al., 2006) and implies that haze particles are sufficiently abundant in the troposphere for methane condensation at any time. The relative humidity is calculated with respect to liquid CH_4—N_2 down to the freezing point of mixture and with respect to solid CH_4 at lower temperatures (Tokano et al., 2006).

2.2.2. Precipitation and evaporation of rain

Excessive methane is immediately converted to precipitation and is rained out. Graves et al. (2008) showed that the fate of falling methane raindrops should depend on the environmental ethane humidity. If the ethane humidity in the troposphere is high, it is possible to stabilize the methane and ethane in the raindrops, so they do not evaporate on the way to the surface.

The ethane mixing ratio in the troposphere is unknown from observations, in contrast to that in the stratosphere. However, several indirect lines of evidence suggest that the tropospheric ethane humidity may be substantial. The GCM of Rannou et al. (2006), which includes methane and ethane condensation, predicts a typical ethane mixing ratio of 2.5×10^{-6} in the lower troposphere, corresponding to relative humidities between 30% and 90% depending on the temperature. There is evidence that light drizzle reaches the surface at least in the equatorial region (Tokano et al., 2006; Ádámkovics et al., 2007). This would only be possible if the ethane humidity is high (Graves et al., 2008). Also the temporal change of darkness of Ontario Lacus suggests that rainfall can reach the surface near the south pole as well (Turtle et al., 2009). Therefore, the model tacitly assumes that the ethane humidity in the troposphere is everywhere high, so falling methane rain does not evaporate.