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Variations in Titan's dune orientations as a result of orbital forcing

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ABSTRACT

Wind-blown dunes are a record of the climatic history in Titan's equatorial region. Through modeling of the climatic conditions associated with Titan's historical orbital configurations (arising from apsidal precessions of Saturn's orbit), we present evidence that the orientations of the dunes are influenced by orbital forcing. Analysis of 3 Titan general circulation models (GCMs) in conjunction with a sediment transport model provides the first direct intercomparison of results from different Titan GCMs. We report variability in the dune orientations predicted for different orbital epochs of up to 70°. Although the response of the GCMs to orbital forcing varies, the orbital influence on the dune orientations is found to be significant across all models. Furthermore, there is near agreement among the two models run with surface topography, with 3 out of the 5 dune fields matching observation for the most recent orbital cycle. Through comparison with observations by Cassini, we find situations in which the observed dune orientations are in best agreement with those modeled for previous orbital configurations or combinations thereof, representing a larger portion of the cycle. We conclude that orbital forcing could be an important factor in governing the present-day dune orientations observed on Titan and should be considered when modeling dune evolution.

1. Introduction

Titan's equatorial region is dominated by dunes. These dunes are unique in the Solar System for both their extensive spatial coverage (Le Gall et al., 2011) and inferred organic composition (Barnes et al., 2008). The interaction of these bedforms with surface winds makes them especially valuable for reconstructing Titan's climate over a significant fraction of the surface. Information about Titan's near-surface winds is of utility both for understanding surface evolution (Lorenz et al., 2006; Tokano, 2010) and planning future exploration (Lorenz, 2008; Barnes et al., 2012).

Important information about the surface wind regime has been provided by studies of the morphologic characteristics of the dunes. Lorenz et al. (2006) indicated that the dunes are predominantly linear in nature, with such dunes typically associated with a dominant sediment transport direction along the axis of the dunes. Examination of the streamlining, or divergence and reconvergence, of these bedforms around topographic obstacles suggests exclusively eastward transport (Lorenz et al., 2006; Radebaugh et al., 2008; Lorenz and Radebaugh, 2009).

Despite the observational evidence for eastward transport which would be driven by westerlies (that is winds blowing from west to east), all general circulation models (GCMs) consistently predict easterly flow to dominate in the near-surface of Titan's equatorial region (Tokano, 2010; Lebonnois et al., 2014; Lora et al., 2015). This seeming contradiction between the direction of wind flow governing sediment transport, and that necessary for conserving atmospheric angular momentum has lead to numerous studies that attempt to reconcile the wind regime with eastward transport of dune material. Lorenz et al. (2006) suggested a tidally driven azimuthal component to the winds that could result in

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eastward transport; however results from a GCM indicated that a complete rotation of the dominant equatorial wind due to tidal influences was not possible (Tokano, 2010). In Tokano (2010), GCM simulations produced fast westerly winds during equinoctial passage of the intertropical convergence zone. Despite their rare occurrence, these westerlies are faster than the easterlies and could in turn dominate sediment transport. Lucas et al. (2014) and Charnay et al. (2015) show that low latitude methane storms around equinox may produce strong westerlies by coupling the strongly superrotating winds aloft with the near-surface flow.

Despite the ability of these mechanisms to reconcile the dune propagation direction with the wind regime, they provide no constraints on the timescales necessary for equilibration of the dune orientations with changes to the wind regime. Investigation of the timescales necessary for the reorientation of Titan's dunes, based on estimates of crestline propagation rates, suggests timescales of order 50,000 years or greater (Lorenz, 2014; Ewing et al., 2015). Therefore, any of the previously indicated mechanisms which produce eastward dune propagation must consistently operate over a timescale greater than this. This finding also calls into question whether effects on the wind regime whose duty cycle is comparable to these reorientation timescales, specifically that of orbital precessions, could impact the dunes. The notion of dunes responding to an orbitally forced climate, even being in equilibrium with winds from a historical orbital epoch, has previously been indicated in terrestrial fieldwork where the largest dunes in the western Sahara Desert have been inferred to be oriented with respect to fast winds from the Last Glacial Maximum (Lancaster et al., 2002), and the dunes of the Gran Desierto Dune Field in Mexico have been dated to several different eras from the last glacial cycle (Beveridge et al., 2006). In the case of Titan, variations in Saturn's orbit affect Titan's climate (Lora et al., 2014), and this must be considered in studies of Titan's dunes. This forcing, which we refer to as Titan's Croll–Milankovitch cycles, has previously been tied to Titan's global-scale geomorphology in the suggestion of its governing Titan's polar lake distributions (Aharonson et al., 2009; Lora et al., 2014).

We present here the first investigation of the response of Titan's dunes to climatic variations driven by the Croll–Milankovitch forcing. This is accomplished through simulations of Titan's climate at historical and modern orbital configurations using three different GCMs, in conjunction with a sediment transport model. We find that regardless of which GCM is chosen, the orbital configuration affects the dune orientation, with as high as 70° variations in the dune orientation as a function of the orbital epoch. The inclusion of topography in the models is found to be important in generating eastward propagation of the dunes, and results in agreement with observation for three out of the five major dune fields for the two models run for the most recent orbital cycle. Although in certain situations a specific orbital epoch or combination thereof is found to be in best agreement with observation, there is no particular epoch that is universally in agreement with observation. We nonetheless demonstrate that the effect of orbital variations on the climate through changes in the solar insolation pattern is important for the prediction of dune orientations, and suggest that future modeling work which includes second order effects beyond the insolation changes may point to specific epochs or time periods that are in best agreement with the orientations observed today.

2. Methods

2.1. Orbital parameters

Variations in the perihelion passage, eccentricity and spin axis of Saturn's orbit affect Titan's climate (Lora et al., 2014). We note that the estimated obliquity of Titan itself with respect to Saturn is small at 0.3° (Stiles et al., 2008), not expected to vary significantly due to tidal locking, and is therefore ignored. Saturn's orbital parameters over the past 1 Myr (years always refers to Earth years unless otherwise specified) were solved for through integration of the SWIFT orbital position code (Levison and Duncan, 1994), along with calculation of obliquity changes through secular theory (Ward and Hamilton, 2004). The results suggest that Saturn's apsidal precessions and eccentricity variations, and not changes in obliquity, dominate variations in the solar insolation pattern at Titan—with up to a 1.4 AU difference between perihelion and aphelion, and complete cycling in the solar longitude of perihelion (L_{sp}, i.e. the time of season at which perihelion occurs). The calculation of orbital parameters in this work is identical to that described in Aharonson et al. (2009) and Appendix A of Lora et al. (2014), to which the reader is referred for a detailed treatment.

Because we quantify the influence of these orbital variations on the surface winds and dune orientations through computationally intensive GCM runs, a small but representative number of specific orbital configurations must be selected for study. We choose to focus on the four configurations for which the L_{sp} coincides with the solstices and equinoxes (referred to hereon as orbital extrema, Fig. 1a). For the two solstitial configurations, the locations of maximum solar insolation are maximally separated (i.e. in closest proximity to the south pole for $L_{sp} = 270^\circ$, vs. the north pole for $L_{sp} = 90^\circ$). As such, the changes in wind directions between these configurations are expected to be maximized (see Section 2.3.3). This cycling of L_{sp} occurs over a period of 45 kyr. We focus on the most recent cycle of the past 45 kyr, noting that the current orbital configuration in which southern summer occurs close to perihelion is most similar to the extremum of 2 kyr ago (we will refer to the orbital extremum of 2 kyr ago as the modern configuration). Note that the eccentricity of Saturn's orbit changes over this period as well, i.e. the perihelion distance also changes. Thus although the insolation patterns of the equinoctial extrema are equivalent, due to differences in the perihelion distance the total amount of solar radiation received varies for the autumnal and vernal equinox configurations.

We also consider a significantly longer cycle of order 1 Myr over the course of which each of the four extrema in L_{sp} of perihelion coincide with Saturn's maximum eccentricity of 0.09 (Fig. 1b).

2.2. General circulation model (GCM) descriptions

We run our simulations of the climatic conditions associated with these orbital extrema using three global, 3D GCMs: the Köln GCM (Tokano et al., 1999; Tokano, 2010), TitanWRF (Newman et al., 2011), and the Titan Atmospheric Model (TAM, Lora et al. (2015)). This is to identify those trends that are independent of the chosen model, and also investigate any model-dependent behavior. The models are described here briefly, although for greater detail the reader is referred to the indicated papers specific to each GCM. It is noted that all models use constant albedos and thermal inertias.

2.2.1. Köln GCM

The Köln GCM uses the Aries/GEOS dynamical core (Suarez and Takacs, 1994), and the radiative transfer scheme of McKay et al. (1989). The model extends up to 250 km altitude and includes 60 vertical layers, the lowest being at an altitude of 300 m. Its horizontal resolution is 11.25° longitude by 7.5° latitude. The surface roughness assumed by the model is 0.005 m, along with a thermal inertia value of 300 $\mathrm{J\,m^{-2}\,s^{-1/2}\,K^{-1}}$. The GCM is described in detail in Tokano 2008 and the references therein.