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Planetary-scale waves locally enhance precipitation on Titan

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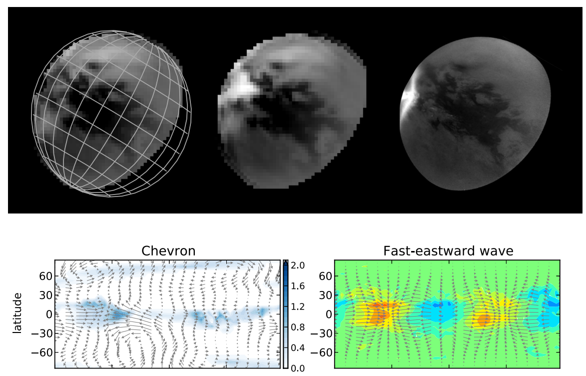
Abstract

We develop a process for the physical interpretation of individual observed storms and their aggregate effect on surface erosion through a combined analysis of cloud observations and simulations. We demonstrate that planetary-scale Kelvin waves naturally arising in a new, three-dimensional version of our Titan general circulation model (GCM) robustly organize convection into chevron-shaped storms at Titan's equator during the current season, as observed [1]. The phasing of this mode with another, much slower one causes a 20-fold increase in precipitation rates over the average, each producing up to several centimeters of precipitation over 1000-km-scale regions, with important implications for observed fluvial features [2].

1. Introduction

Titan exhibits an active weather cycle involving methane [3]. A recent cloud outburst indicated a close interplay between high- and low-latitude cloud activity mediated by planetary-scale waves [4]. Because of low insolation and a stabilizing antigreenhouse effect [5], moist convection on Titan cannot be maintained purely through surface evaporative fluxes, indicating that moisture convergence provided by large-scale modes of circulation is important for convective cloud formation [6, 7].

Recent Cassini Imaging Science Subsystem (ISS) images of Titan have revealed large-scale clouds with an interesting array of morphologies and characteristics [1]. Most strikingly, an arrow-shaped cloud oriented eastward was observed at the equator on 27 September 2010 [1], followed by observations of surface wetting which gradually diminished over several months [8]. We now use our fully three-dimensional Titan GCM to illuminate the dynamical origin of these storms, and we develop a methodology for comparing model precipitation rates to cloud observations. Our approach represents the genesis of a new field of dynamic meteorology on Titan.



2. Simulating cloud observations

Cloud opacity depends on the sizes and amount of suspended, condensed methane, and therefore provides the only observable constraint on the amount of liquid (and/or solid) methane produced by storms. While our Titan GCM does have a moist convection scheme which predicts a surface precipitation rate, the model does not predict the formation of individual clouds. We assume precipitation due to convection is likely to be associated with the most optically thick clouds observed. A small number of physically motivated assumptions allow us to simulate cloud opacity in ISS bands using the GCM's precipitation field, thereby quantitatively linking cloud opacity to the amount of precipitation. Simulated observations of an event during the equinoctial transition of our GCM is displayed in the top-center panel of the figure. The arrow-shaped cloud observed by Cassini ISS is shown in the top-right panel of the figure [1], demonstrating that our Titan GCM produces convective storms with the basic morphology of the cloud observation. The dynamics underlying this storm is illustrated through diagnostics of the GCM.

3. Dynamic meteorology of Titan storms

The bottom-left panel of the figure shows the surface wind field with the zonal mean subtracted (arrows) and the 15-day cumulative precipitation (blue, cm) of the event shown in the top-center panel. The cumulative precipitation of this storm indicates greatly enhanced precipitation rates compared to the global- and time-mean of less than 0.1 mm/day. A chevron precipitation feature at 100° longitude at the equator is spatially coincident with a region of horizontal convergence of surface winds, indicating a role for gravity waves. The chevron produces one to two centimeters of precipitation over a 2000-km-wide region during its lifetime, an amount sufficient to create runoff and erosion of the equatorial surface [9]. Chevron-shaped storms represent the dominant mode of variability of the GCM during the current Titan season.

To isolate the spatial structure of the dominant mode, we perform empirical orthogonal function (EOF) analysis on the simulation. The spatial structure and phase speed (12 m s^{-1}) of the leading EOF corresponds closely to that of a baroclinic, equatorially-trapped Kelvin wave. The spatial patterns of precipitation and surface wind anomaly of this mode are shown in the bottom-right panel of the figure. Crucially, these waves are associated with roughly chevron-shaped equatorial precipitation patterns. Thus, convective storms in the GCM are organized by large-scale modes of variability, and the modes are robustly associated in a statistical sense with precipitation structures resembling observed clouds.

4. Summary and Conclusions

We have developed a process for interpreting morphologies of and precipitation associated with Titan's clouds through a combined analysis of observations and GCM simulations, thereby opening a new field of dynamic meteorology. We find that recent cloud activity near Titan's equator just following NSE is consistent with the presence of the dominant mode of atmospheric variability in the GCM. A fast, eastward-propagating mode traveling at $\sim$12 m s^{-1} with the character of an equatorially-trapped Kelvin wave produces chevron-shaped precipitation patterns similar to the cloud observed by Cassini ISS on 27 September 2010 [1]. The mode produces several centimeters of precipitation over 1000-km-scale regions, locally enhancing precipitation rates by 20-fold over the mean, and therefore plays a crucial role in fluvial erosion of Titan's surface. Observations clearly indicate surface changes associated with the equatorial chevron [8].

Acknowledgements

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