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Winds and tides of Ligeia Mare, with application to the drift of the proposed time TiME (Titan Mare Explorer) capsule

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ABSTRACT

We use two independent General Circulation Models (GCMs) to estimate surface winds at Titan's Ligeia Mare (78° N, 250° W), motivated by a proposed mission to land a floating capsule in this ~500 km hydrocarbon sea. The models agree on the overall magnitude (~0.5–1 m/s) and seasonal variation (strongest in summer) of windspeeds, but details of seasonal and diurnal variation of windspeed and direction differ somewhat, with the role of surface exchanges being more significant than that of gravitational tides in the atmosphere. We also investigate the tidal dynamics in the sea using a numerical ocean dynamics model: assuming a rigid lithosphere, the tidal amplitude is up to ~0.8 m. Tidal currents are overall proportional to the reciprocal of depth—with an assumed central depth of 300 m, the characteristic tidal currents are ~1 cm/s, with notable motions being a slosh between Ligeia's eastern and western lobes, and a clockwise flow pattern.

We find that a capsule will drift at approximately one tenth of the windspeed, unless measures are adopted to augment the drag areas above or below the waterline. Thus motion of a floating capsule is dominated by the wind, and is likely to be several km per Earth day, a rate that will be readily measured from Earth by radio navigation methods. In some instances, the wind vector rotates diurnally such that the drift trajectory is epicyclic.

1. Introduction

The Titan Mare Explorer (TiME—Stofan et al., 2010) is a Discovery mission concept, recently proposed to NASA. The concept was initially developed in a NASA-funded Discovery and Scout Mission Capability Enhancement (DSMCE) study which sought to explore affordable mission concepts that would be enabled by an efficient long-lived power source, the Advanced Stirling Radioisotope Generator (ASRG), a unit that provides ~100 W of electrical power from ~500 W of heat evolved from plutonium decay. Such a unit allows long-lived operation at Titan, where both the thermal power and electrical power are required and solar power is impractical. The goals of the TIME mission are to measure the composition of the liquid in Ligeia and to observe atmospheric and oceanic phenomena at the air:sea interface (e.g. evaporation, generation of wind-driven waves) with cameras and a suite of meteorology and physical properties instrumentation, including a depth sounder.

The TiME mission features a launch in 2016, with direct entry from its interplanetary trajectory into Titan's atmosphere in July 2023. After parachute descent and splashdown into Ligeia Mare, it would operate for a nominal duration chosen (not limited by power or geometry) to be 6 Titan days. The vehicle communicates direct to Earth and, in principle, it could be possible to maintain at least intermittent contact for several years after arrival: the Earth finally sinks below the horizon as seen from Ligeia in 2026.

It is of interest to consider how far and fast the vehicle may move on the surface of Ligeia, to determine if or when approach to a shoreline can be anticipated, to estimate the length of a likely sonar depth profile, and to assess what environmental factors can be estimated by measuring the drift. To that end, this paper summarizes model information on winds and tides. Although these model studies were motivated by the TiME mission, they will be of interest for studies of Titan oceanography in that winds may yield observable wave roughness as well as azimuthal variations in shoreline morphology. We begin, however, with a brief introduction to Ligeia observations by Cassini to date.

2. Observations and morphology

Ligeia Mare (Fig. 1) was first identified in the Cassini T25 Synthetic Aperture Radar (SAR) image acquired on February 27, 2007 and parts were re-observed on T28 and T29 six and eight weeks later: the corresponding Titan season, described by the

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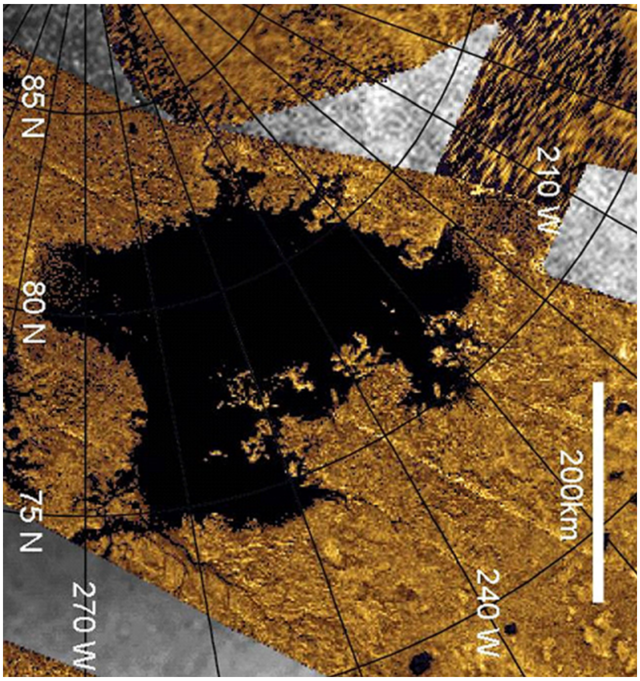

Fig. 1. Polar stereographic projection of a mosaic of Cassini SAR images (gold), showing the T-shaped Ligeia Mare.

Solar Longitude L_s, is $L_s=331^\circ$, about two thirds of the way between Northern Winter Solstice ($L_s=270^\circ$) and Northern Spring Equinox ($L_s=0^\circ$).

As with other Titan lakes (e.g. Stofan et al., 2007; Paillou et al., 2008), Ligeia is very dark in the SAR images, suggesting a very smooth surface. Radiometry data (Janssen et al., 2009) indicate a brightness temperature of 88.5 K, consistent (assuming a physical temperature of $\sim$90–92 K) with a flat surface with a dielectric constant of 1.7 ± 0.1, as would be expected with a liquid ethane/methane composition. Unlike the shallow margins of Ontario Lacus in the south, where an appreciable bottom echo can be detected (Hayes et al., 2010), almost all of Ligeia is pitch-black to the radar observations above (a striped appearance in raw images is due to the different noise floor in the images used to make the radar mosaic).

Morphologically, Ligeia seen with the 270° W meridian vertical (north up) is roughly T-shaped, with a West branch, an East branch and a South branch. Several large river channels appear to drain into Ligeia, most notably at the SouthWestern corner (75° N, 265° W) and at the northernmost point (80° N, 240° W). Overall the outline is of a ria coastline, indicative of a geologically recent rise in liquid level such that river valleys are drowned: the existence of many islands (particularly on the Southeastern side) is also consistent with this picture. A couple of somewhat straight edges on the Western side attest to possible tectonic influences on the outline. The geological history of Ligeia, therefore, appears complex and thus the mechanism by which the basin was formed in the first place is not obvious. The stippled appearance at the northwestern corner suggests (by analogy with Ontario Lacus) that this area may be shallow.

The largest radar-dark (and therefore likely deep) region is centered at about 80° N, 245° W: a 100 km circle centered on this point has $>99\%$ of radar pixels (averaged over 1 km areas) below -13 dB, and thus likely liquid-covered. Over 95% of the pixels thus defined are darker than -20 dB, and thus (by analogy with Ontario Lacus bathymetry) are greater than 6 m deep. A fuller analysis of all the available radar data (some areas of Ligeia have been observed 2–3 times, at different incidence angles) will be the subject of future work.

Ligeia is also visible in the 2 μm VIMS mosaic in Brown et al. (2008) although the resolution is too poor to learn anything new. Similarly, it can be identified in the 938 nm mosaic by Turtle et al. (2009). However, these early images under far-from-ideal conditions show promise for new findings as new and better observing opportunities arise in the Cassini Solstice mission as the subsolar latitude increases in the next few years. (In fact it is interesting to note that atmospheric scattering permitted the detection of Ligeia's outline in these optical observations even though it was close to, or even beyond, the geometric terminator.)

As Titan's second-largest sea, Ligeia is a significant contributor to Titan's organic inventory (Lorenz et al., 2008). The composition of Ligeia Mare is not known, although it is presumably dominated by ethane and methane. A near-infrared spectroscopic signature of ethane was detected in Ontario Lacus (Brown et al., 2008) although it is not clear if that constituent is dominant there, nor whether the composition of northern seas should be the same as Ontario, since seasonal or Croll–Milankovich astronomical forcing (Aharonson et al., 2009) may favor a more volatile composition in the north in the present epoch. The composition of Titan seas in thermodynamic equilibrium with the atmosphere (assuming the 5% methane mixing ratio in the equatorial atmosphere applies at the poles) is 76–79% ethane (Cordier et al., 2009). However, some disequilibrium is possible due to thermal inertia effects (e.g. Tokano, 2009a, 2009b) and methane evaporation from the sea surface (e.g. Mitri et al., 2007), so the composition may be more or less ethane-rich.

3. Winds

We simulate the winds on Ligeia with a three-dimensional atmospheric GCM that is coupled to a one-dimensional sea energy balance (thermal stratification) model, as described in Tokano (2009a) and hereafter referred to as the 'Köln (Cologne) model'. The atmospheric model solves a set of primitive equations (with hydrostatic approximation) on gridpoints to predict the temporal evolution of the wind, surface 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. The 3-dimensionality of the model enables modeling of breeze induced by temperature contrasts between the sea area and the surroundings. The prescribed seas are assumed to have a lower albedo and higher thermal inertia than the surrounding dry land. (The sea is assumed to have an albedo half as large as land. The thermal inertia of the sea is dependent on the composition and instantaneous temperature, but is 2–3 times larger than that assumed for land. The sea energy balance model predicts the sea surface temperature considering absorption of sunlight, emission of thermal infrared radiation, sensible heat flux between sea and air, latent heat of evaporation and convective mixing.

As discussed in Tokano (2009a), there is a significant effect of the assumed sea composition on the predicted meteorology. Specifically, if the sea is methane-rich, methane evaporation absorbs much of the incident solar energy and leads to gentler large-scale winds than for an ethane-rich composition where the sunlight is converted more into sensible heat. In this paper, we