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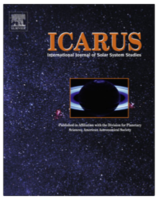

Atmospheric tides in Gale Crater, Mars

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ABSTRACT

Atmospheric tides are the primary source of daily air pressure variation at the surface of Mars. These tides are forced by solar heating of the atmosphere and modulated by the presence of atmospheric dust, topography, and surface albedo and thermal inertia. This results in a complex mix of sun-synchronous and non-sun-synchronous tides propagating both eastward and westward around the planet in periods that are integer fractions of a solar day. The Rover Environmental Monitoring Station on board the Mars Science Laboratory has observed air pressure at a regular cadence for over 1 Mars year and here we analyze and diagnose atmospheric tides in this pressure record. The diurnal tide amplitude varies from 26 to 63 Pa with an average phase of 0424 local true solar time, while the semidiurnal tide amplitude varies from 5 to 20 Pa with an average phase of 0929. We find that both the diurnal and semidiurnal tides in Gale Crater are highly correlated to atmospheric opacity variations at a value of 0.9 and to each other at a value of 0.77, with some key exceptions occurring during regional and local dust storms. We supplement our analysis with MarsWRF general circulation modeling to examine how a local dust storm impacts the diurnal tide in its vicinity. We find that both the diurnal tide amplitude enhancement and regional coverage of notable amplitude enhancement linearly scales with the size of the local dust storm. Our results provide the first long-term record of surface pressure tides near the martian equator.

1. Introduction

From Mariner 9 through the Mars Reconnaissance Orbiter (MRO) and the Mars Science Laboratory (MSL), atmospheric observations of Mars have illuminated the major role of suspended mineral dust in controlling atmospheric temperatures and hence modifying the atmospheric circulation. Increased atmospheric dust opacity is responsible for producing a deeper meridional overturning circulation (Haberle et al., 1982; Wilson, 1997; Newman et al., 2002a, 2002b) and altering the phases and amplitudes of thermal tides (e.g., Leovy and Zurek, 1979). Viking lander observations of surface air pressure, atmospheric tides, and the response of those tides to varying atmospheric dust loadings has served as the foundation for much of Mars atmospheric science in the last 3 decades. The long, multiple Mars Year (MY) duration of the Viking landers make them unique to-date. The seminal works of Leovy and Zurek (1979) and Zurek and Leovy (1981) firmly established the coupling of Mars atmospheric dynamics and dust opacity. The complexities and nuances of this coupling continue to be studied today.

The Mars Science Laboratory (MSL) Rover Environmental Monitoring System (REMS) is the most capable and longest-lived surface weather station on Mars since the Viking landers. REMS is a suite of instruments measuring temperature, pressure, wind, surface temperature, downward ultraviolet flux, and humidity (Gómez-Elvira et al., 2012) at the rover's location. The REMS dataset has already produced considerable insight into the nature of the environment in Gale Crater (e.g., Haberle et al., 2014; Harri et al., 2014; Gómez-Elvira et al., 2014; Hamilton et al., 2014; Martínez et al., 2014; Martín-Torres et al., 2015).

Unlike the Viking landers, which landed at middle northern latitudes, MSL and REMS are located very near the equator. While this

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precludes REMS from observing the baroclinic traveling waves common to the higher latitudes (i.e., the familiar low- and high-pressure systems of terrestrial weather reports), daily variations in the tropical latitudes are heavily dominated by tides (Wilson and Hamilton, 1996).

Atmospheric tides are a response to the diurnal cycle of solar heating. They are manifested as planetary-scale inertia-gravity waves and are additionally modified and forced by varying surface properties (e.g., topography and thermal inertia) and atmospheric aerosol loading. Chapman and Lindzen (1970) described the formal mathematics of Laplace's Tidal Equations and their solutions (known as Hough functions). As Leovy and Zurek (1979) showed and numerous further studies have elucidated (e.g., Leovy, 1981; Wilson and Hamilton, 1996; Bridger and Murphy, 1998; Guzewich et al., 2014), the observed features of Mars atmospheric tides are closely tied to atmospheric dust loading. More recent work has shown that tides are also sensitive to water ice aerosol loading (Kleinböhl et al., 2013; Wilson and Guzewich; 2014; Wilson et al., 2014). Tides can be divided into two broad groups: migrating tides and non-migrating tides. The primary difference between these groups is that the migrating tides are westward-propagating and sun-synchronous, while the non-migrating tides can be westward- or eastward-propagating and are not sun-synchronous.

The manifestation of an individual atmospheric tide (e.g., the migrating diurnal tide) in the atmosphere is the result of the superposition of a combination of Hough function solutions, each solution having its own meridional and vertical structure. The lowest-order Hough function solution is known as the "gravest" mode. Additionally, each Hough function (due to their varying meridional and vertical structures) responds uniquely to forcing mechanisms such as the presence, horizontal and vertical extents, and opacity of atmospheric dust and water ice. For example, the gravest Hough mode of the migrating diurnal tide exhibits is equatorially-trapped (Chapman and Lindzen, 1970; Wilson and Hamilton, 1996; Guzewich et al., 2012) and thus is insensitive to dust aerosol forcing at higher latitudes. The vertical wavelength of the gravest Hough mode of the migrating diurnal tide is also relatively small (approximately 32 km) and hence is more sensitive to how dust is distributed in the vertical column. The gravest Hough mode of the migrating semidiurnal tide, however, is meridionally-broad with a very long vertical wavelength (100–200 km) and responds efficiently to global aerosol loading (e.g., Bridger and Murphy, 1998) while being relatively insensitive to local dust heating. Indeed, the amplitude of the migrating semidiurnal tide has even been used to estimate globally-averaged aerosol loading (Zurek, 1980; Zurek and Leovy, 1981; Lewis and Barker, 2005; Wilson et al., 2008). Tidal theory suggests that the properties of the migrating diurnal tide at a given surface location (i.e., REMS observing air pressure in Gale Crater) is a combination of several Hough modes while the migrating semidiurnal tide is predominantly represented by the gravest Hough mode (Chapman and Lindzen, 1970).

In this work, we present an analysis of atmospheric tides in Gale Crater, Mars, as observed by the REMS air pressure sensor. In Section 2, we discuss the REMS data and our methodology for analyzing atmospheric tides, as well as providing some background information on the MarsWRF general circulation model (GCM), which we use to contextualize and extend our data analysis. Section 3 provides the analysis of tides in REMS pressure measurements, while Section 4 links that analysis to the atmospheric aerosol opacity. Section 5 compares the observed tides in Gale Crater with analysis of MarsWRF output. Section 6 focuses on the occurrence of a local dust storm near Gale Crater, and through the aid of MarsWRF simulations, connects the atmospheric response of this storm to tidal theory. Finally, Section 7 concludes the paper.

2. Data and methodology

2.1. REMS observations

The REMS air pressure sensor is located inside the body of the Curiosity rover and can measure pressure at a cadence of 1–0.01 Hz (Gómez-Elvira et al., 2012). In typical planning for a sol of MSL operations, REMS is scheduled to conduct 5-min duration "background" observations at the top of each hour (local Mars solar time, LMST) and periodic hour-long (and occasionally longer) "extended" observation blocks. The timing of these extended observations is decided according to a rotating cadence, such that all times of sol are typically observed at least once in any 6-sol period (Gómez-Elvira et al., 2014). Harri et al. (2014) discusses the REMS pressure sensors in great detail and preliminary interpretation of the first observations by these sensors was described by Haberle et al. (2014). The reader is referred to the above works for in-depth discussion of the workings of the REMS pressure sensors. In the frequency range (diurnal through quadiurnal) discussed in this study the most significant error mode is the temperature hysteresis that causes <±0.75 Pa "repeatability variation" (Harri et al., 2014). Even if the magnitude of this artificial signal is sometimes proportional to the amplitudes of the terdiurnal and quadiurnal tides (Section 3), it has been shown that even in the worst case it has practically no effect on the amplitudes (<0.25 Pa uncertainty) and phases (phase variations typically of <5 min) of the four first harmonics of the daily pressure variation (H. Kahanpää, REMS Team Meeting, May 20, 2014). These uncertainties are significantly lower than the 8 Pa discretization error in Viking data (e.g., Tillman et al., 1993). Thus, we ignore the instrument uncertainty factors for the remainder of this discussion.

In this paper we use the time convention of areocentric solar longitude (shortened to "L_s") and the Mars Year notation of Clancy et al. (2000) which defines $L_s = 0°$ of Mars Year 0 (MY0) on April 11th, 1955. $L_s = 0°$ of a given Mars Year occurs at northern hemisphere spring equinox. Note for reference that times can be indexed by "MSL Year", counted from MSL's landing on August 6th, 2012. Hence, MSL Year 1 runs from MY31 $L_s = 150.5°$ to MY32 $L_s = 150.5°$.

The data used in this study (version 1.0 of the REMS reduced data records) was not available in the Planetary Data System at the time of analysis, but is now available at http://atmos.nmsu.edu/PDS/data/mslrem_1001/.

2.2. Tide analysis

The REMS background cadence ensures that pressure is always measured over the first 5 min of every hour. These regular observations are most useful for analyzing atmospheric tides. For each hour, we average the pressure measurements for those first 5 min, to produce 24 data points for a given sol. We then perform a Fourier transform on this time sequence of air pressure (for each individual sol) to obtain the amplitudes and phases of each individual tide frequency. We refer to these frequencies as "diurnal" (once-per-sol), "semidiurnal" (twice-per-sol), "terdiurnal" (thrice-per-sol), and "quadiurnal" (four-times-per-sol). At a given single-station observing point, the time sequence of air pressure can be represented as the sum of a harmonic series of components, each with a frequency that is an integer fraction of a solar day:

$$S(p) = \sum_n s_n(p)$$

where $S(p)$ represents air pressure and n represents each individual harmonic component. Furthermore, we assume that each component can be represented as: