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Planetary boundary layer and circulation dynamics at Gale Crater, Mars

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ABSTRACT

The Mars implementation of the Planet Weather Research and Forecasting (PlanetWRF) model, MarsWRF, is used here to simulate the atmospheric conditions at Gale Crater for different seasons during a period coincident with the Curiosity rover operations. The model is first evaluated with the existing single-point observations from the Rover Environmental Monitoring Station (REMS), and is then used to provide a larger scale interpretation of these unique measurements as well as to give complementary information where there are gaps in the measurements.

The variability of the planetary boundary layer depth may be a driver of the changes in the local dust and trace gas content within the crater. Our results show that the average time when the PBL height is deeper than the crater rim increases and decreases with the same rate and pattern as Curiosity's observations of the line-of-sight of dust within the crater and that the season when maximal (minimal) mixing is produced is L_s 225°–315° (L_s 90°–110°). Thus the diurnal and seasonal variability of the PBL depth seems to be the driver of the changes in the local dust content within the crater. A comparison with the available methane measurements suggests that changes in the PBL depth may also be one of the factors that accounts for the observed variability, with the model results pointing towards a local source to the north of the MSL site.

The interaction between regional and local flows at Gale Crater is also investigated assuming that the meridional wind, the dynamically important component of the horizontal wind at Gale, anomalies with respect to the daily mean can be approximated by a sinusoidal function as they typically oscillate between positive (south to north) and negative (north to south) values that correspond to upslope/downslope or downslope/upslope regimes along the crater rim and Mount Sharp slopes and the dichotomy boundary. The smallest magnitudes are found in the northern crater floor in a region that comprises Bradbury Landing, in particular at L_s 90° when they are less than 1 m s^{-1}, indicating very little lateral mixing with outside air. The largest amplitudes occur in the south-western portions of the crater where they can exceed 20 m s^{-1}. Should the slope flows along the crater rims interact with the dichotomy boundary flow, which is more likely at L_s 270° and very unlikely at L_s 90°, they are likely to interact constructively for a few hours from late evening to nighttime (∼17–23 LMST) and from pre-dawn to early morning (∼5–11 LMST) hours at the norther crater rim and destructively at night (∼22–23 LMST) and in the morning (∼10–11 LMST) at the southern crater rim.

We conclude that a better understanding of the PBL and circulation dynamics has important implications for the variability of the concentration of dust, non-condensable and trace gases at the bottom of other craters on Mars as mixing with outside air can be achieved vertically, through changes in the PBL depth, and laterally, by the transport of air into and out of the crater.

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1. Introduction

The Planetary Boundary Layer (hereafter PBL) is the part of the atmosphere closest to the surface, within which the interactions between the atmosphere and the surface take place. On Mars it is in this region where dust is lifted and settles back to the surface, where water and other trace molecules may be transferred between the surface and the atmosphere, and where turbulence and small-scale features such as convective vortices and topographic flows occur (Petrosyan et al., 2011). Dust is a fundamental component of the atmosphere on Mars that has a strong impact on its thermal and dynamical state. It affects the operation of surface spacecraft as well as the retrieval from orbiters and it is also critical for the entry, descent and landing phase of surface spacecraft probes. Despite its central importance, to date the circulation within this region of the atmosphere has been poorly validated due to the scarcity of in-situ instruments on the surface of Mars. The goal of this work is to investigate the PBL and circulation dynamics on daily and seasonal time-scales to better understand their variability and potential implications for: (1) the concentration of trace gases such as methane; (2) the dynamics of dust, and; (3) the interaction between regional and local slope flows. The Martian implementation of the Mars Weather Research and Forecasting (MarsWRF) model (Richardson et al., 2007) is used here to simulate the atmospheric conditions at Gale Crater for different seasons during a period coincident with the Curiosity rover operations. The model will be first validated with the existing single-point observations from Curiosity, and will then be used to provide a larger scale interpretation of these unique measurements as well as to provide complementary information where there are gaps in measurements.

On August 6th 2012 (UTC), the Mars Science Laboratory (MSL) mission successfully landed and delivered the rover Curiosity to the surface on Mars at 4.49°S, 137.42°E, in the north-western part of Gale Crater, a 154 km wide crater located at the edge of the hemispheric dichotomy, whose floor is at 4.451 km below datum. The central mound of Aeolis Mons (Mount Sharp) rises about 5.5 km above the floor of the crater (Anderson and Bell, 2010). Gale is an impact crater that is estimated to have formed ~3.6–3.8 billion years ago (Thompson et al., 2011). On board the MSL rover is the Rover Environmental Monitoring Station (REMS; Gómez-Elvira et al., 2012, 2014) which comprises several sensors including air and ground temperature sensors, a pressure sensor, an ultraviolet (hereafter UV) sensor with 6 detectors and a wind sensor. Being the only surface observation station in the region (and one of only two rovers currently operating on the planet), REMS measurements have proven to be very useful and have been used for a wide variety of purposes including to gain further insight into the properties of some of the soil types present on Mars (e.g. Martínez et al., 2014; Hamilton et al., 2014), to perform dust (Moore et al., 2016), moisture (Savijärvi et al., 2015) and pressure (Haberle et al., 2014; Ullán et al., 2017) studies and to investigate the chemical composition of the surface and subsurface and the possible viability of transient liquid water (Martín-Torres et al., 2015). This dataset has also been used to evaluate the performance of numerical models (e.g. Pla-García et al., 2016; Rafkin et al., 2016) that investigate the influence of the atmospheric circulation dynamics on local scales. More recently, in Newman et al. (2017) REMS data have been used to verify the performance of MarsWRF during the season of the Bagnold Dunes Campaign, as well as to constrain the setup and assumptions used in the model.

A discussion of the meteorological conditions at Gale is given in Rafkin et al. (2016). Outside the dust storm season (which typically begins around L_s 180°–225° and ends around L_s 315°–360°; L_s is the areocentric solar longitude) the circulation at Gale is dominated by upslope (downslope) flows along Mount Sharp and the crater rim during the day (night). In the daytime the winds diverge from the bottom of the crater and converge higher up with descent in the middle of the crater which acts to suppress convection and reduce the depth of the boundary layer (Tyler and Barnes, 2013; Moores et al., 2015). At night the downslope winds do not typically reach the bottom of the crater as at some point in their descent the compressed air parcels will be warmer than the air below and hence will lose their negative buoyancy. At this point they flow horizontally, gliding over the colder air below and forming katabatic sheets. As a result, the air at the bottom of the crater remains largely isolated with very little mixing with the outside air. In the dust storm season these local circulations are likely to be disrupted by the global mean meridional circulation: the large-scale northerly winds favour the downslope flow along the northern crater rim leading to strong mixing with the air from outside the crater in what is known as a “flushing” event (Rafkin et al., 2016). The global mean meridional circulation is stronger in the austral summer primarily due to: (i) the asymmetry in the solar insolation (in the austral summer the insolation is up to 45% greater than in the boreal summer leading to a stronger Hadley circulation; Zurek et al., 1992); (ii) the hemispheric dichotomy (as the northern one-third of Mars is at a lower elevation than the bottom two-thirds of the planet, in the boreal winter the lower surface temperatures in the northern polar region lead to higher surface pressures that together with the elevated terrain in the southern hemisphere and associated lower surface pressures enhance the global mean meridional circulation (Hourdin et al., 1993; Joshi et al., 1995; Richardson and Wilson, 2002); and (iii) the increased amount of dust in the atmosphere in the austral summer compared to the boreal summer that acts as a positive feedback strengthening the Hadley cell (Forget et al., 1999).

In this paper, a Martian atmospheric numerical model is run for Gale Crater with the model performance evaluated against observational data given by REMS. The primary focus is on the diurnal cycle of the PBL depth in the different seasons during a Martian year. Since the landing of Curiosity at Gale Crater, REMS, the Navigation Cameras (Navcam) and Mastcam have provided two and a half Martian Years (MY, the convention of Clancy et al. (2000) is used in this work) of observations of the Martian dust cycle from the surface (Moore et al., 2016). We hypothesize that the PBL height variability may be the driver of the dust content variability within the crater as well as of the variability of other trace molecules such as methane, which has been measured with variable concentration during the year at the crater floor (Webster et al., 2013, 2015). As we shall see in this work, even if the maximum depth of the PBL exceeds the height of the crater rim, vertical mixing with the outside air will be limited by the period of time during which it is deeper than this height (i.e. the temporal extension of the daytime convective boundary layer). Another topic discussed here is circulation dynamics, with a focus on the interaction between the crater slope flows and the regional-scale flows. While variations in the PBL depth will affect the extent of the vertical mixing of the air inside the crater with that outside, changes in the horizontal circulation will determine the amount of lateral transport of air into and out of the crater. By accounting for the full three-dimension circulation, further insight into the variability of dust and trace gases such as methane can be gained. In addition to the global mean meridional circulation (which is expected to impart southerly winds around L_s 90°, northerly winds around L_s 270° and weak and variable winds at the equinoxes), the circulation at Gale is controlled by local slope flows and regional slope flows. The latter, and besides the dichotomy boundary flow (which is expected to be significant as Gale is located at the edge of the hemispheric dichotomy), includes slope flows from neighbouring topographic features such as Elysium Mons located to the north. The local and regional slope flows generally blow