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Detection of Northern Hemisphere transient eddies at Gale Crater Mars

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ABSTRACT

The Rover Environmental Monitoring Station (REMS) on the Curiosity Rover is operating in the Southern Hemisphere of Mars and is detecting synoptic period oscillations in the pressure data that we attribute to Northern Hemisphere transient eddies. We base this interpretation on the similarity in the periods of the eddies and their seasonal variations with those observed in northern midlatitudes by Viking Lander 2 (VL-2) 18 Mars years earlier. Further support for this interpretation comes from global circulation modeling which shows similar behavior in the transient eddies at the grid points closest to Curiosity and VL-2. These observations provide the first in situ evidence that the frontal systems often associated with "Flushing Dust Storms" do cross the equator and extend into the Southern Hemisphere.

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1. Introduction

Dust raising frontal systems in the Northern Hemisphere of Mars have been observed in imaging data (Cantor et al., 2001; Wang et al., 2003, 2005) and are theoretically predicted (Hollingsworth and Kahre, 2010). They are generally associated with traveling synoptic scale baroclinic weather systems and are thus primarily confined to mid northern latitudes during the fall, winter, and spring seasons (e.g., Barnes, 1980). Occasionally these systems appear to trigger dust lifting at low latitudes of the Southern Hemisphere suggesting that their frontal systems extend across the equator. Wang et al. (2003) give an example and propose a link between some of these equator-crossing systems to regional scale dust lifting events facilitated by favorable phasing with the thermal tide. Thus, dust-raising frontal systems are an integral part of the modern Martian dust cycle.

We report here the detection of these synoptic weather systems in the pressure data acquired by the Rover Environmental Monitoring Station (REMS) on the Mars Science Laboratory's (MSL) Curiosity Rover (see Grotzinger et al. (2012) for the mission description and Gomez-Elvira et al. (2012) for a description of the REMS payload). Curiosity is operating in the Southern Hemisphere within Gale Crater at 4.5° S, 137.4° E and thus the REMS data are providing direct in situ confirmation that the pressure fields associated with traveling weather systems in the Northern Hemisphere of Mars can extend across the equator into the Southern Hemisphere. While we expect broader geographic extent on Mars compared to Earth,[1] the regularity of equator crossing systems on Mars is unique compared to Earth where such crossings are rare.

We base our interpretation primarily on the striking similarity of the frequencies (periods) and seasonal variations of synoptic period disturbances (i.e., disturbances with periods between ~2 and 12 Sols) in the REMS data with that from Viking Lander 2 (VL-2) at 48.3° N, 134.0° E. Although the amplitudes observed by MSL are greatly diminished compared to VL-2, there is a clear correlation between the two sites that is most easily explained by equator crossing systems. VL-2 is best suited for this comparison because of all previous landers with pressure sensors (the others being VL-1, Pathfinder, and Phoenix), VL-2 is located at a midlatitude Northern Hemisphere site where there is a strong signal and good seasonal coverage. Furthermore, the disturbances at VL-2 have been studied extensively (Ryan et al., 1978; Tillman et al., 1979; Barnes, 1980, 1981) and are attributed to baroclinic instability of the mean flow (e.g., Barnes, 1984), a characterization well-

[1] The Rossby radius of deformation is the appropriate length scale for baroclinic eddies and it is about the same for Mars as it is for Earth (~1000 km). Thus, relative to the size of the planet, Martian eddies should have a greater zonal and meridional extent (see, for example, Zurek et al., 1992; Zurek, 2017; or Read and Lewis, 2004).

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supported by a variety of independent modeling studies (Barnes et al., 1993; Hollingsworth et al., 1996, 1997, 2011; Collins et al., 1996; Forget et al., 1999; Wilson et al., 2006; Wang et al., 2013). And while the data sets were not acquired simultaneously (VL-2 operated during MY 12 and 13 while MSL began operations in MY 31), baroclinic eddies are a seasonally recurring feature of Martian weather and are present at northern midlatitudes every year from fall through spring (see reviews by Zurek et al. (1992) and Barnes et al. (2017)). From a statistical perspective, therefore, we might expect similar characteristics from year to year with the exception, of course, for those years with major planet encircling dust events, as was the case during MY 12 (see, for example, Haberle et al., 1982).

We provide further support for the connection between the REMS disturbances and those at VL-2 with our own climate modeling work. In this case, we use a well tested and recently validated version of the Ames Mars Global Climate Model (GCM) with updates as described in Haberle et al. (2018). As in the observations the model shows strong similarities in the seasonal behavior of the eddies at each site and even suggests their influence may extend further into the Southern Hemisphere than Gale Crater. Taken together, our analysis indicates that REMS is detecting Northern Hemisphere baroclinic eddies that extend across the equator into the Southern Hemisphere.

2. Data sources

MSL began operations on August 6, 2012 at $L_s = 156°$ and data are now available for more than two Mars years. VL-2 began operations on September 3, 1976 at $L_s = 118°$ and ended operations ~1.5 MY later on VL-2 sol 1050 at $L_s = 348°$. We analyze and compare these data sets for all seasons where there is overlap. To simplify working between these data sets we use a continuous L_s counter where values greater than 360° signify a second (or third) year depending on the actual value.

2.1. REMS data

Gómez-Elvira et al. (2012) describe the REMS payload. Harri et al. (2014) and Haberle et al. (2014) summarize the details of its pressure sensors. The data used here, available from the PDS, were taken from Barocap 1 of Oscillator 2 and have an absolute accuracy of <3 Pa at the beginning of the mission, a resolution of 0.2 Pa (set by the instrument noise), and a diurnal repeatability of ±0.75 Pa. The REMS sampling strategy emphasized regular hourly 5-min measurements acquired at 1 Hz supplemented by movable hour long “extended blocs” commandable on a daily basis. For this barocap, we have not removed warm-up errors (which are quite small <0.07%) nor have we corrected for Rover elevation changes. For the almost 2 Mars years we analyze, the Rover elevation increased steadily by ~ 75 m. A 75-m increase in elevation corresponds to a fractional decrease in pressure of <1%. Such a change spread out uniformly over two Mars years will not alias the much shorter periods we focus on in this paper. Thus, neglecting elevation changes will not affect our conclusions.

Two data sets were constructed from these measurements: a binned hourly data set with 24 regularly spaced values each sol, and a daily averaged data set constructed from the binned data provided all 24-hourly bins were populated. In practice, missing data are rare on the MSL mission and hourly binned data and daily averages are available for almost every sol.

2.2. VL-2 data

Chamberlain et al. (1976) describe the Viking meteorology sensors. Both landers had identical meteorological payloads. The Viking Tavis pressure sensors were capacitance devices with an accuracy of ~2 Pa and a resolution of 8.8 Pa set by the readout digitization (Tillman et al., 1993).[2] The sampling strategy was much less regular than MSL having variable sampling rates, times of day, and block durations. For pressure, 100–300 nearly uniformly spaced samples were collected each sol (Barnes, 1980). These data were binned and averaged into 25 equal time bins per sol from which daily averages were computed. Short data gaps (several hours) in the binned data were filled with a cubic spline, or by using data from adjoining sols. Longer gaps were not filled. Daily averages were not computed for sols with more than 6 hours of missing data (Tillman et al., 1993). These data are available from the PDS and were prepared by Murphy (1989) and Tillman (1989).

2.3. GCM

We use the latest version of the Ames Mars GCM which has been significantly updated since the last detailed description given in Haberle et al. (1999). Some updates can be found in Haberle et al. (2003). More recent brief updates are given by Kahre et al. (2015), Hollingsworth et al. (2017), and Kahre et al. (2017a). A more comprehensive discussion of the full set of model algorithms and performance is in preparation and will be submitted soon (Haberle et al., 2018).

The latest version of the model includes a water cycle with a complete treatment of cloud microphysics and radiatively active clouds. Dust lifting at the surface tracks the MY 24 dust climatology of Montabone et al. (2015)—a year with no global dust storms. Once in the atmosphere the dust is radiatively active and transported by the predicted wind fields. Thus, the dust vertical distribution is self-consistently determined rather than prescribed. Diabatic heating and cooling rates include contributions due to radiation, convection, and latent heat release of CO_2. Visible and infrared radiative heating rates are calculated from a 2-stream code using correlated-k's that accounts for gaseous absorption by CO_2 and H_2O, and aerosol scattering and absorption by dust particles and water ice clouds. Boundary layer mixing of heat, momentum, and tracers is parameterized using a stability dependent diffusive mixing scheme (see Haberle et al., 1999). Surface properties are taken from MOLA topography (Smith et al., 1999), and the albedo and thermal inertia of Putzig and Mellon (2007) with modifications described in Tyler and Barnes (2014). The model runs at 5° × 6° (lat/long) resolution with 24 vertical layers that increase in thickness from ~10 m near the surface to ~5 km at the top (~70 km). The model warm starts from a common simulation and runs for 10+ Mars years. It equilibrates after ~5 Mars years. Here, we use model output for the 10th year of the warm start simulation. The model shows reasonable agreement with the observed seasonal and latitudinal variations of zonal mean water vapor and cloud column abundances, and was tuned (by adjusting the depth to ground ice and the CO_2 cap albedo and emissivity) to give a good match to the seasonal variation of the Viking Lander daily averaged surface pressures.

The most important update to the model relevant to this work is the inclusion of radiatively active water ice clouds. During northern winter the polar hoods cool the atmosphere and increase the equator to pole temperature gradients in the lower atmosphere. This intensifies baroclinic wave activity and broadens the meridional reach of the eddies and hence their ability to cross the equator. On the other hand, the model horizontal resolution is inadequate to resolve Gale Crater and thus cannot account for the crater circulation and how it might interact with equator crossing ed-

[2] See parenthetical statement at the bottom of page 10,966 of Tillman et al. (1993).