Icarus 427 (2025) 116367

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Note

Quasi-Biennial Oscillation absent in Mars atmospheric reanalysis datasets

J. Michael Battalio

Department of Earth and Planetary Sciences, Yale University, New Haven, CT, USA

ARTICLE INFO

Dataset link: https://doi.org/10.21954/ou.rd.c.4278950, https://doi.org/10.18113/D3W375

Keywords:
Mars
Mars, Atmosphere
Meteorology

ABSTRACT

Mars's atmosphere shares many of the same types of oscillations exhibited in Earth's climate, like the Semiannual Oscillation and Annular Modes, but using two Martian reanalysis datasets derived from Mars Climate Sounder observations, we find that Mars fails to generate a Quasi-Biennial Oscillation (QBO). The lack of a QBO may stem from the absence of a stratosphere on Mars — as the background flow is critical for setting the altitude that vertically propagating waves deposit momentum — or the extreme latitudinal variation of the overturning circulation disrupts waves sources. The lack of a QBO on Mars may enable unique comparisons between Earth's and Mars's atmospheres.

1. Introduction

The development of reanalysis datasets for the Martian atmosphere over the last decades has enabled the description of several types of climate variability in the winds known to exist on Earth (Battalio et al., 2025). Mars supports annular modes in both hemispheres that control the position and strength of the mid-latitude, eddy-driven jet streams that appear in the troposphere below 100 Pa (Battalio and Lora, 2021). The annular mode results from interactions between the eddy momentum fluxes and the zonal-mean flow (Battalio and Lora, 2021). Mars also has a Semi-annual oscillation (SAO) concentrated equatorward of 30° between 20–60 km or about 100–1 Pa (Ruan et al., 2019), which is primarily forced by seasonal variations in advection from the thermally direct meridional circulation (Ruan et al., 2019).

Until now, the existence of a Martian oscillation that is similar to Earth's Quasi-Biennial Oscillation (QBO) was unclear. Earth's QBO was discovered in the 1950s using rawinsonde observations and is now reasonably well-modeled in general circulation models (GCMs) and captured in Earth reanalyses [for a review of the QBO including the historical perspective, see Baldwin et al. (2001)]. The QBO consists of alternating bands of eastward (to the east) and westward (to the west) winds that propagate downward towards the surface from a height of ~35 km or 10 hPa, with a period of approximately 28 months. Earth's QBO is caused by the deposition of momentum by waves that progressively break at decreasing altitudes due to the acceleration of the zonal-mean wind caused by their breaking (Plumb, 1977; Pahlavan et al., 2021), and the precise population of waves helps set a period that can range over shorter windows between 26–30 months (Baldwin et al., 2001). The presence of a Martian SAO and the coupling of the QBO and SAO in Earth's atmosphere (Garcia et al., 1997; Smith et al., 2017) prompt a search for any quasi-periodic oscillation in Mars's tropical winds not tied to the annual cycle.

2. Methods

Two Martian reanalysis datasets have greater than 4 Mars years of data. With currently available instrumentation, the Open access to Mars Assimilated Remote Soundings (OpenMARS v1.0) (Holmes et al., 2020) and Ensemble Mars Atmospheric Reanalysis System (EMARS, v1.0) (Greybush et al., 2019) both assimilate Mars Climate Sounder (MCS) retrievals from the Mars Reconnaissance Orbiter (Kleinböhl et al., 2009). MCS observes twice-daily (~0300 and 1500 local time) limb profiles of temperature at 105 vertical level resolution. MCS observations begin at Mars Year (MY) 28 at areocentric longitude L_s = 112°. EMARS extends to MY 33, L_s = 105°, and OpenMARS continues until the start of MY 36. OpenMARS assimilates observations using an analysis correction scheme (Lewis et al., 2007) on the UK version of the LMD Mars GCM (Forget et al., 1999) on a 5°×5° horizontal grid with 25 sigma levels every two Mars hours. EMARS is an ensemble dataset with 16 members and uses a local ensemble transform Kalman assimilation scheme (Greybush et al., 2012). The ensemble mean is shown here, but the individual member is similar. EMARS uses the Geophysical Fluid Dynamics Laboratory Mars GCM (Wilson and Hamilton, 1996) at 6° longitude × 5° latitude horizontal resolution with 28 hybrid sigma-pressure levels at hourly temporal resolution. The vertical coordinate of both datasets is interpolated to pressure coordinates. We only investigate the MCS-era of both datasets due to MCS's sensitivity of the middle atmosphere (Kleinböhl et al., 2009) and because the longer duration of the MCS-era enables the creation of a more robust yearly climatology.

The variability of the zonal wind with height in the Martian equatorial latitudes is determined by first taking the diurnal average of the zonal wind from each reanalysis to remove the tides; then, the

E-mail address: michael@battalio.com.

https://doi.org/10.1016/j.icarus.2024.116367
Received 28 August 2024; Received in revised form 18 October 2024; Accepted 2 November 2024
Available online 21 November 2024

zonal average is taken. The SAO is diagnosed by subtracting the zonal wind averaged across ±30°N on each vertical level from the zonal-mean zonal wind at each particular latitude. This procedure obtains the QBO for Earth reanalysis data (not shown) (Baldwin et al., 2001; Pahlavan et al., 2024) but does not for Mars. Removal of a yearly climatology is necessary for Mars to ensure that a QBO-ike signal is not overwhelmed by a large amplitude SAO. A daily climatology of the zonal winds is calculated by finding the median value for the winds at a given altitude for a particular sol of the Martian year from all the available Mars years. The median rather than the mean is used to account for the highly anomalous impact of large regional dust events (Kass et al., 2016; Montabone et al., 2015, 2020; Battalio and Wang, 2021; Battalio et al., 2023b; Wang et al., 2023), which would otherwise skew the climatology. MY 28 and 34 are excluded from the zonal wind climatology due to the occurrence of global-scale dust events, as are all times for which some MCS data were not available for assimilation into the reanalyses. The climatology is subtracted from the original diurnal, zonal-mean field on a sol-by-year basis to arrive at a climatological anomaly field of zonal winds. The data are averaged equatorward of ±30°N; reducing the range over which the winds are averaged by 20° does not substantively impact the results. Finally, the data are linearly detrended. For Earth, the QBO is apparent without removing the climatology because the QBO is so large and is at a lower altitude than the SAO (Pahlavan et al., 2024).

3. Middle atmosphere anomalous zonal-wind

The average anomalous zonal winds defined as deviations from the average vertical profile of the zonal wind in the Martian tropical atmosphere from OpenMARS are shown in Fig. 1a. (EMARS is not shown but is similar.) The clearest repeating signal is the twice yearly SAO within 40–60 km altitude, as previously described in models (Kuroda et al., 2008) and reanalysis (Ruan et al., 2019), with a positive phase at the start of each Mars year and around $L_s = 180°$. The SAO routinely achieves magnitudes of 20 m s^{-1} and robustly repeats with limited inter-annual variability owing to the strong forcing of the meridional circulation by the seasonal cycle (Ruan et al., 2019). The largest deviations from the yearly cycle are caused by MCS data gaps, indicated by right-slanted hatching in Fig. 1, or during the MY 34 global dust event, indicated by left-slanted hatching. Any large anomalies during, immediately preceding, or immediately following gaps in data should be considered unreliable and most likely due to the assimilation scheme jerking the analysis back to observations before or after a data gap. The only large anomaly with data coverage occurs throughout MY 29, particularly in the middle of the year, but may be related to the very strong "Z" or Aonia-Solis-Valles dust storm season that year (Battalio and Wang, 2019). The inter-annual variability of large regional dust events may modulate the zonal wind to some extent, but the duration of wind anomalies in Fig. 1b and c is substantively shorter than the influence of the events on extra-tropical temperatures (Kass et al., 2016), for example.

The highly repeating pattern of the SAO enables its signal to be robustly removed by subtracting the yearly zonal-mean wind climatology, shown in Fig. 1b for OpenMARS and Fig. 1c for EMARS. Outside of the times noted as also having greater SAO interannual variability, westward or eastward zonal-mean wind anomalies never surpass 10 m s^{-1} below 50 km and rarely reach 15 m s^{-1} above 60 km. When observations are available, the climatologically anomalous zonal-mean winds have no overarching periodicity and possess a quasi-random structure. Above 80 km altitude, the reanalyses become poorly constrained, but below this altitude, wind anomalies align between the beginning of MY 30 and end of EMARS. For example, an eastward (positive) anomaly occurs in both reanalyses around MY 30.6 at altitudes between 60–80 km, and a westward (negative) anomaly occurs around MY 32.6 between 60–80 km height. This agreement between reanalyses increases the confidence that the datasets are observation-constrained and that Mars truly lacks a QBO. Interestingly, these two sets of anomalies occur at roughly the same time of year but in opposite directions, so the SAO is effectively removed by removing the climatology. External mechanisms or forcing features to the middle atmosphere circulation may generate these anomalies.

A power spectrum of the timeseries of data at 60 or 30 km height approximates red-noise signal at $p < 0.05$ (not shown) except for a single peak around 180 sols for the 30 km spectrum, which is far less than a Mars year of 668 sols. The signal above 668 sols has generally less power than red noise. These heights are selected as being at the top and bottom of the SAO zone, respectively, and the lowest altitude of the SAO is generally considered the initiation level of the QBO for Earth (Baldwin et al., 2001; Smith et al., 2017).

4. Potential reasons for QBO absence

An obvious question is why Mars lacks a QBO. Mars's unique general circulation provides at least three potential explanations for the absence of the wave forcing required to maintain the QBO. First, Mars lacks an ozone layer and stratosphere. For Earth's QBO, the stratosphere provides a critical layer for the breaking of gravity, inertial, and Rossby waves that deposit the alternating eastward and westward momentum driving the QBO, due to changes in the background wind profile (Baldwin et al., 2001). Without this layer, some waves may continue propagating upward (Mayr et al., 2000; Yang et al., 2012). This potentially explains why the forcing of Mars's SAO, which is at higher altitudes, includes additional wave modes not usually found to force Earth's SAO, in particular gravity waves (Ruan et al., 2019).

A second possibility is that the extreme yearly latitudinal variation of the Martian inter-tropical convergence zone disrupts gravity wave sources of momentum. The Hadley circulation on Mars flips between a one-cell configuration during solstice seasons and a two-cell configuration during equinoctial seasons (Barnes et al., 2017) due to a combination of the short radiative timescale and small planetary radius of Mars (Guendelman and Kaspi, 2022; Williams et al., 2024). The QBO on Earth is generally considered to influence the troposphere and not vice versa (Andrews, 1987; Baldwin et al., 2001); however, some of the wave forcing of Earth's QBO comes from deep convection associated with ascending branch of the Hadley cell (Salby and Callaghan, 2007; Liess and Geller, 2012). Mars's shifting of the ascending branch of the Hadley cell and convection away from the tropics for large portions of the year removes a source of gravity waves that may be important for the QBO generation (Dunkerton, 1997; Pahlavan et al., 2024).

A third possibility is that the infrequent global dust events are so highly disruptive that they prevent the formation of coherent middle-atmosphere oscillations not directly tied to the seasonal cycle like the SAO. For example, global dust events disrupt baroclinic Rossby waves (Kuroda et al., 2007; Battalio et al., 2016), enhance super-rotation at Mars's equatorial latitudes, (Rajendran et al., 2021), and modulate gravity waves (Barnes, 1990; Kuroda et al., 2020; Heavens et al., 2022; Wu et al., 2022; Shaposhnikov et al., 2022; Battalio et al., 2023a; Pankine et al., 2024) and convective instability in the middle atmosphere (Heavens et al., 2023). The continual perturbation of wave sources and wind profiles could interfere with the regular reversal of momentum fluxes needed to generate alternating wind directions.

5. Summary and conclusions

Mars seems to lack a Quasi-Biennial Oscillation (QBO) — defined as a tropical circulation that has a periodicity longer than a year — as quantified using a methodology that accurately replicates Earth's QBO. Two observation-constrained reanalysis datasets agree on the placement and timing of the Semi-annual Oscillation (SAO) in the mesosphere and of zonal-wind anomalies with the SAO removed, raising confidence in the absence of a Martian QBO. A power spectrum of the anomalous zonal-mean wind finds significant power only at

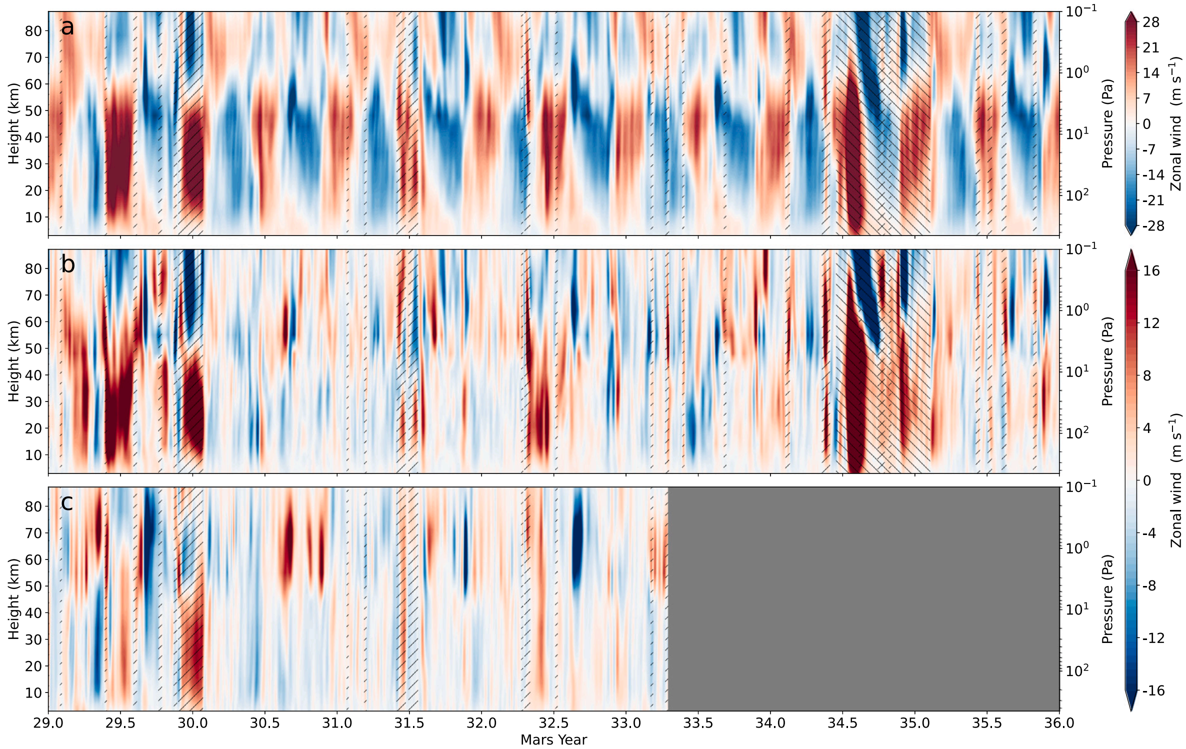

Fig. 1. Seasonal variation of the anomalous zonal-mean zonal wind averaged between 30°S–30°N for (a, b) OpenMARS and (c) EMARS. In panel a, the zonal-wind anomalies are defined by subtracting the average profile of the zonal wind only. For panels b and c, the zonal-wind climatology is removed in addition to removing the average zonal wind profile. The plots are smoothed by removing variability with a period of less than 20 sols. Right-slanted hatching indicates times when MCS observations were unavailable for more than 1.5 consecutive sols, and each model ran freely. Left-slanted hatching denotes the time of the MY 34 global dust event. The gray shading in panel c shows years not yet available in EMARS. Height on the left *y*-axis is a pseudo-height defined from a 10 km scale height and reference surface pressure of 610 Pa.

180 sols, far below a QBO periodicity, but the limited duration of the reanalyses prevents the quantification of oscillations greater than roughly 5 Mars years. The absence of a Martian QBO may be related to Mars's unique circulation and atmospheric structure, in particular Mars's superrotation, latitudinal extremes in the ascending branch of the Hadley circulation, and lack of a stratosphere. Future research should focus on modeling studies to determine the precise reason or reasons. Given the importance of the QBO in Earth's momentum budget, the lack of a Martian QBO makes Mars an interesting case study for how other types of climate variability interact without a QBO to provide a teleconnection between the upper and lower or tropical and extratropical atmosphere.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Battalio is supported by NASA Mars Data Analysis Program Grant #80NSSC21K1095. Juan M. Lora and two anonymous reviewers provided helpful comments on the manuscript.

Data availability

The OpenMARS reanalysis is available at https://doi.org/10.21954/ou.rd.c.4278950. The EMARS reanalysis is available at https://doi.org/10.18113/D3W375.

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