A COMPARISON OF ANNULAR MODES ON MARS AND EARTH.

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Zonally symmetric, or annular, climate variability is important for describing patterns in circulation and precipitation in Earth's atmosphere, but there has been limited work to establish its importance for Mars. We show that Mars has equivalent annular modes that are more important for describing climate variability than Earth's modes. Mars's modes resemble Earth's with one that describes the north-south movement of the jet stream and another that describes pulsation of waves. Just as Earth's modes link to precipitation, Mars's annular modes may aid understanding of dust storm growth.

Annular modes are hemispheric modes of climate variability that result from internal atmospheric dynamics[1;2]. Climate variability is "annular" if its structure of variability is zonally *symmetric*, i.e., if there are positive covariances between all longitudes of a given meteorological field at a given latitude[3]. Through an investigation of annular dynamics, one can get at many different dynamical phenomena, including the jet stream and storm tracks[4]. Mars presents a particularly peculiar case of zonal-mean dynamics, with annular structures previously recognized. For example, Mars's polar vortex is annular with a ring of westerly winds around the pole and an annulus of elevated potential vorticity[5].

Two Types of Annular Modes

Two annular modes exist within the atmospheres of Mars and Earth. The barotropic annular mode is the most important source of climate variability in the middle and high latitudes, explaining about $\sim$30% of the variance in the zonal-mean wind and geopotential height[6], and is called the U-AM. The U-AM is defined using empirical orthogonal function (EOF) analysis of anomalous (i.e., non-seasonal) shifts in atmospheric mass between the polar regions and the middle latitudes, which can be characterized by the surface pressure[2] or zonal-mean wind[4]. The associated wind field vacillations arise from the movement of atmospheric mass, schematically shown in Fig. 1. An index (the first principal component) defines times when the zonal-mean jet (Fig. 1, top, labeled contours) moves poleward or when anomalous low pressure resides over the poles, denoted as the positive phase[6]. When the U-AM is regressed onto the zonal wind, a vertically uniform dipole emerges (Fig. 1, shading), which reflects the poleward (red arrow) and equatorward (blue arrow) motion of the eastward jet during the positive and negative polarity phases, respectively. The vertical uniformity of the wind signature (a barotropic structure) and importance of momentum fluxes give the U-AM its name[4].

The second annular mode is prescribed by the first EOF of eddy winds (eddy kinetic energy, EKE-AM). On Earth, this mode explains 34% of the variance in the zonal-mean EKE[4]. The mode is positive when there are positive anomalies in the EKE, meaning extra-tropical storms are amplified (Fig. 1, bottom), and is called the baroclinic annular mode. The vertical non-uniformity and wind-shear along with heat fluxes across the midlatitudes demonstrate the baroclinic nature of this mode[4].

Because the processes behind the two types of annular modes are different, their associated timescales are different. These timescales reflect how the annular modes evolve as a result of the dynamics controlling their behavior. Earth's U-AM peaks at low frequencies, meaning that the mode varies on the order of months[6]. Conversely, Earth's EKE-AM peaks at a 25 day period, with a drop off at smaller frequencies (longer periods)[4]. This indicates that pulses of EKE can be expected with this 25 day period, which is intrinsically connected to the feedback between dynamic and radiative processes that has been shown to play a major role in the reoccurring nature of Martian dust activity[7–9].

Importantly, the zonal symmetry of annular modes is reflective of real patterns of variability in Earth's atmosphere[3]. For example, the positive phase of the EKE-AM (amplified EKE) is expressed in increased precipitation[10]. Earth's U-AM also exhibits positive relationships to atmospheric observables, for example concentrations of minor species, particularly ozone[6].

Martian Annular Modes

The mere presence of baroclinic waves on Mars[11] suggests the possibility of annular modes[6], but early work relegated a Martian modes to third most important, explaining $<$9% of the surface pressure variance, from two Martian General Circulation Models[12;13]. However, these initial works weighted fields with an improper latitudinal factor. Weighted properly, annular modes with baroclinic characteristics have been shown to exist in the southern hemisphere of Mars[7].

A recent publication in Nature Astronomy (arXiv) fully reveals the importance of annular modes[1]. Much of the variability of the mid-to-high latitude atmospheric flow is explained by Mars's U-AM (Fig. 2a,b) and EKE-AM (Fig. 2c,d). These modes resemble Earth's barotropic and baroclinic annular modes, respectively.

Mars's U-AM explains $\sim$30% of the variance in the anomalous zonal-mean jet stream. As on Earth, these patterns represent latitudinal shifts of the zonal-mean jet (Fig. 1). The Martian U-AM behaves like Earth's barotropic annular modes, which are linked to anomalous zonal-mean eddy momentum flux and are vertically stacked—a barotropic structure. Figure 2i,j shows the regression of anomalous zonal-mean zonal wind and eddy momentum fluxes onto the standardized U-AM principal component. A dipole in the anomalous zonal wind emerges, with positive centers of action around 75°N/S and negative centers at 45°N/S, similar to the

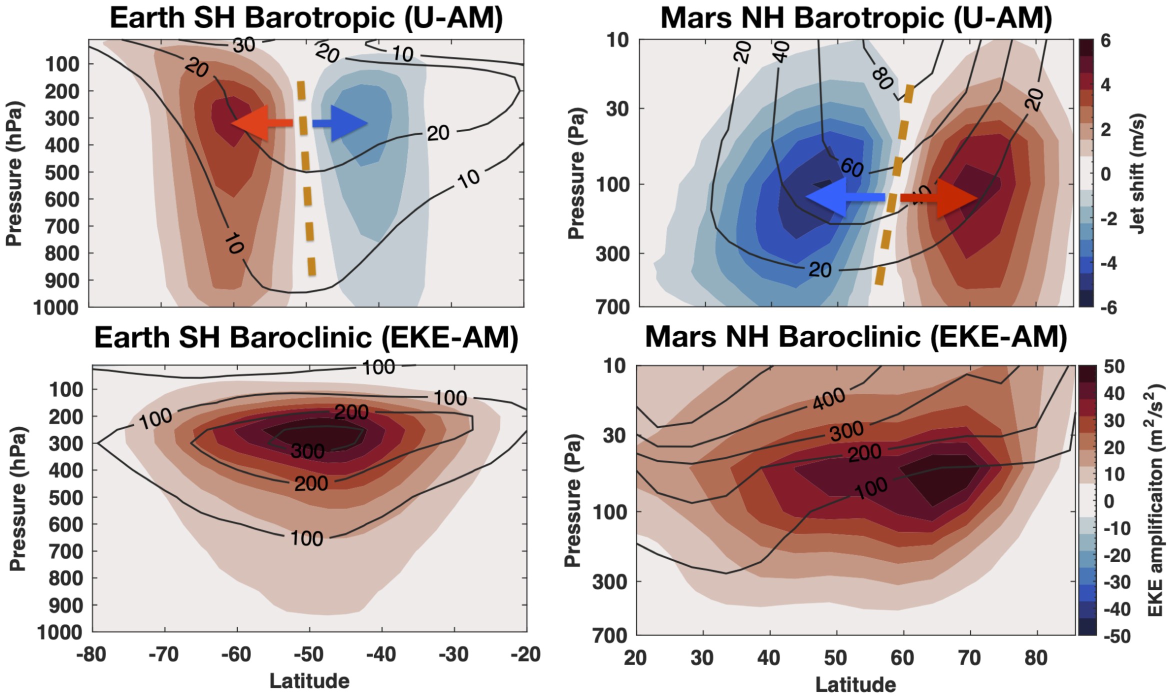

Figure 1: Top: Schematic of the U-AM (filled contours) in the zonal wind (labeled contours, m s^{-1}) for Earth's southern hemisphere (left, ERA-I reanalysis) and Mars's northern hemisphere (right, MACDA reanalysis). The jet shifts during positive (red arrow) or negative (blue arrow) phases across the center of the jet stream (orange dashed line). Bottom: Vertical structure of Earth's southern EKE-AM (filled contours, left), based on the EKE (labeled contours, m^2 s^{-2}) and the equivalent Martian mode (right)[1].

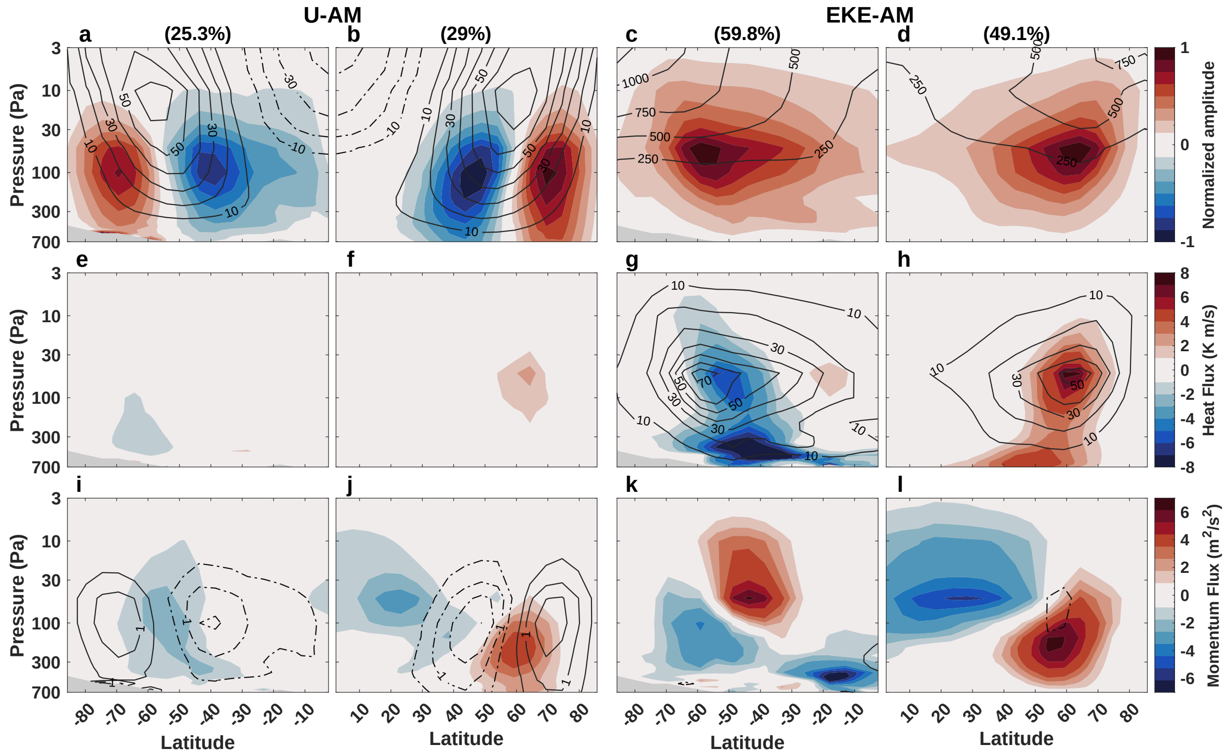

Figure 2: Zonal-mean structure of Mars's annular modes in zonal wind and EKE averaged over MACDA and EMARS. (a–d) the empirical orthogonal function (shading) and zonal wind (a and b) or EKE (c and d). Each pair of columns shows the southern (left) and northern (right) hemispheres. The individual column titles give the percent of variance explained. (e–h) regressions onto the anomalous EKE and eddy heat flux (shading) at a -1 sol lag. (i–l) regressions onto the anomalous zonal wind and horizontal momentum flux at -1 sol lag. Regressions are only shown exceeding 99% confidence. Adapted from Battalio & Lora (2021)[1].

SAM/NAM[6;10]. The anomalous zonal-mean eddy momentum flux regressed onto the U-AM at a -1 sol lag (Fig. 2i,j) closely resembles the terrestrial U-AM, with a maximum of poleward eddy momentum flux located in the node between the mode dipole. Mars's U-AM also resembles the terrestrial barotropic mode when regressed onto surface pressure anomalies (not shown), with anomalous surface pressure exhibiting a minimum at the pole. This reflects the movement of mass away from the pole at times of westerly anomalies in the jet.

Just as Earth's and Mars's U-AMs are similar, Mars's EKE-AM resembles Earth's baroclinic mode[4;10]. Mars's EKE-AM links to anomalous poleward zonal-mean eddy heat fluxes that vary vertically (Fig. 2g,h). The mode is a monopole that overlaps the maximum time-mean EKE and explains 60 and 49% of the anomalous EKE for the southern and northern hemispheres, respectively (Fig. 12c,d), far larger than for Earth[4;10]. The signature of the EKE-AM on the EKE exhibits an annular feature maximized between 60–70°N/S and 10–150 Pa (Fig. 2g,h). This feature is robust in all Mars reanalysis datasets[1].

Midlatitude storm tracks on Mars are linked to the EKE-AM. The anomalous mass-integrated eddy kinetic energy[11] regressed on the EKE-AM peaks mainly at 45–75°N and 15–60°S (Fig. 2c,d). Upstream of Acidalia, Arcadia, and Utopia Planitiae in the northern hemisphere and along Argyre Basin in the southern hemisphere, storm tracks connect most strongly to the EKE-AM (not shown). Each of these regions hosts areas of increased storm activity from transient waves[8;11;14;15].

Earth's baroclinic and barotropic annular modes are decoupled, meaning that there is no correlation between Earth's EKE-AM and U-AM. Earth's EKE-AM is uncorrelated to eddy fluxes of momentum, and Earth's U-AM is uncorrelated to eddy fluxes of heat[4;10]. This is not the case for Mars's modes: Mars's EKE-AM is associated with anomalous fluxes of eddy momentum that are double those related to its U-AM (Fig. 2i–l). Mars's EKE-AM does not regress on zonal-mean zonal wind (nor does Mars's U-AM regress on either eddy heat fluxes or EKE). Thus, Mars's EKE-AM cannot be established as a purely baroclinic mode. The entangled nature of Martian annular modes aligns with eddy energetics analyses[11;14;15] that find that transient eddies grow barotropically as well as baroclinically.

Timescales of the Annular Modes

Only the spatial patterns of variability of the modes have been described so far, but each spatial pattern corresponds to a principal component time series quantifying the magnitude of the mode at each time step. The largest features are spikes due to global dust storms in MYs 25 and 28 (not shown). A yearly cycle is most evident in northern hemisphere EKE-AM, becoming most amplified when transient wave activity is maximized during the fall and winter and displaying a lull during the solstitial pause[15;16]. The power spectrum of the U-AM is red, with an average e-folding time of 41.8±1.5 sols (Fig. 3a), which is considerably larger than Earth's U-AM of 10 days[6]. The northern hemisphere EKE-AM is also approximately red, with an e-folding time of

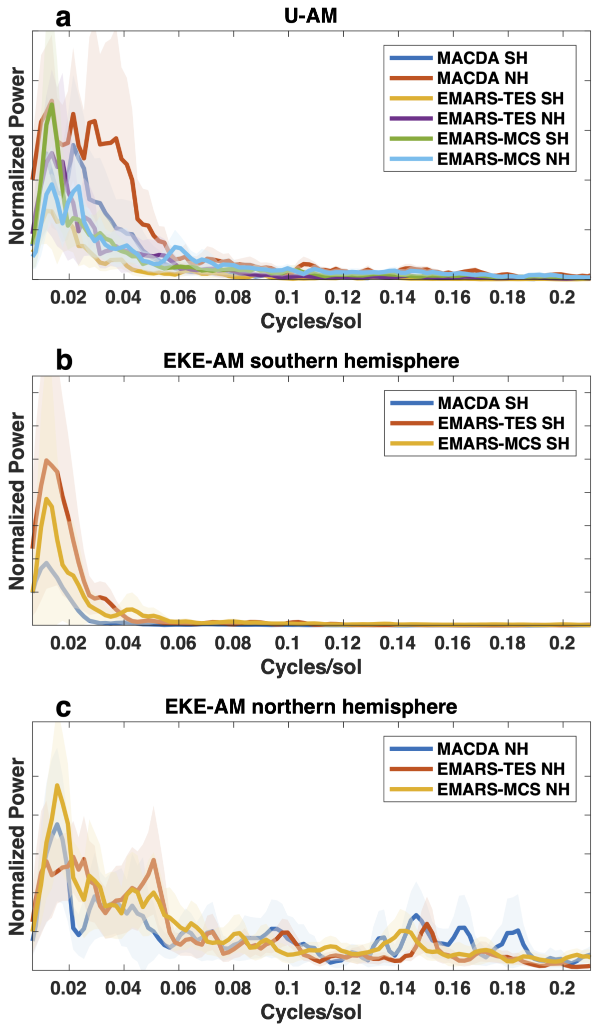

Figure 3: Power spectra of the annular mode principal components for Mars. (a) Spectra from the U-AM. (b) Spectra from the southern EKE-AM. (c) Spectra from the northern EKE-AM. The 95% confidence intervals are shaded.

13.9±1.1 sols (Fig. 3c). There are some indications of elevated power at higher frequencies at 20 sols (0.05 cycles/sol), with additional power around the periods of individual baroclinic waves, or 5–7 sols. The southern hemisphere is dominated by long-period power, with a time-scale of 115±3 sols, arising from the rare occurrence of global dust storms (Fig. 3b). Combined with the finding that the spatial patterns of variability during global dust storms are highly correlated to the patterns without global storms (r<0.95) indicates that global dust storms merely amplify existing spatial patterns of annular variability instead of generating additional modes.

Predicting Dust Storms using Annular Modes

The repeatability of annular modes, particularly Mars's EKE-AM, hints at applications of their dynamics. Dust activity on Mars has been known to exhibit a pulsing character, particularly in the Aonia-Solis-Vallis (ASV)

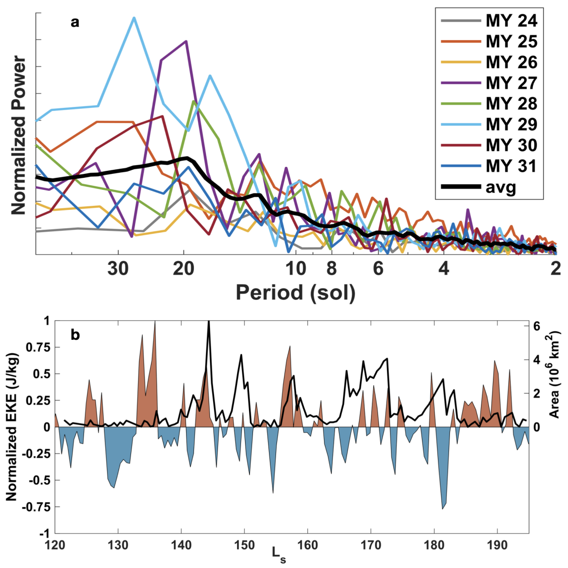

Figure 4: Top: spectra of dust activity in 8 MY from the ASV track. Black line is the average. Bottom: principal component of MACDA southern EKE-AM (filled plot) and ASV dust area from MY 26. Adapted from Battalio & Wang (2019)[7].

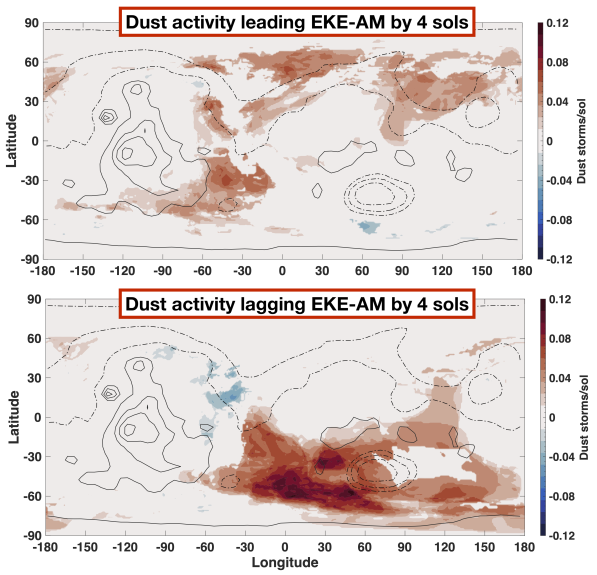

Figure 5: Regression of the northern EMARS EKE-AM from MY 31 on the MDAD. Dust activity (top) leading the EKE-AM by 4 sols and (bottom) lagging the EKE-AM by 4 sols. Regressions performed for L_s=180°–360°. Topography contoured every 2000 m. Adapted from Battalio & Lora (2021)[1].

dust storm track[7]. Dust storms have periodicities of 2–10 sols due to individual baroclinic waves, but the average peak in periodicity occurs at 20 sols (Fig. 4, top). Further, the principal component of the southern EKE-AM correlates with dust storms in the ASV track spring (Fig. 4, bottom).

The repeatability of dust storms also occurs in the northern hemisphere[7–9]. Using the Mars Dust Activity Database (MDAD)[9], the EKE-AM is regressed on dust activity for MY 31. The initiation regions of dust storms (Acidalia, Utopia, Arcadia Planitae, and the ASV track) are indicated when the regression of dust activity leads the EKE-AM (Fig. 5, top). These dust-lifting regions exhibit dust activity before the EKE-AM peaks. This is analogous to the relationship between Earth's EKE-AM and precipitation, as precipitation maximizes one day before the mode maximizes[10].

While precipitation is an instantaneous occurrence, dust on Mars remains lofted—and radiatively important—for weeks, thus, so too can the EKE-AM affect the atmosphere long after it peaks. Reversing the regression order so that dust activity lags the EKE-AM (i.e., the EKE-AM peak precedes the dust), locations into which dust storms evolve have a positive link to the EKE-AM (Fig. 5, bottom). Therefore, sufficient observation of the current state of the EKE-AM may indicate when large dust events are favored before they grow.

Summary

Earth's annular modes quantify zonal-mean climate variability in the mid-latitudes. Mars's annular modes explain greater percentages of variance than Earth's: up to 50%. Mars's barotropic (U-AM) and baroclinic modes (EKE-AM), defined from the zonal-mean zonal wind and zonal-mean eddy kinetic energy, respectively, share many similarities to Earth's. The U-AM describes north-south shifts of the jet stream, and the EKE-AM represents the pulsing nature of transient wave storm tracks. Differences from Earth's annular mode dynamics arise from the mixed baroclinic-barotropic nature of Mars's transient waves[15]. The EKE-AM regresses strongly onto dust activity from the Mars Dust Activity Database[9]. Dust activity in areas where large dust storms initiate leads the mode; areas where dust is transported lag the mode. This indicates that mere observation of the annular modes may permit prediction of major dust events.

Acknowledgments

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References: [1] Battalio et al. 2021, Nat. Astr., 5, 1139. [2] Trenberth et al. 1981, MWR, 109, 1169. [3] Gerber et al. 2017, JAS, 74, 317. [4] Thompson et al. 2014, JAS, 71, 1480. [5] Waugh et al. 2016, JGR:P, 121, 1. [6] Hartmann et al. 2000, PNAS, 97, 1412. [7] Battalio et al. 2019, Icar., 321, 367. [8] Battalio et al. 2020, Icar., 338, 113507. [9] Battalio et al. 2021, Icar., 354, 114059. [10] Thompson et al. 2014, Sci., 343, 641. [11] Battalio et al. 2016, Icar., 276, 1. [12] Leroy et al. 2003, GRL, 30, 1. [13] Yamashita et al. 2007, GRL, 34, 2. [14] Battalio et al. 2018, Icar., 309, 220. [15] Battalio, J. M. 2022, JAS, 79, 361. [16] Lewis et al. 2016, Icar., 264, 456.