Annular modes of variability in the atmospheres of Mars and Titan

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Annular modes explain much of the internal variability of Earth’s atmosphere but have never been identified as influential on other planets. Using data assimilation datasets for Mars and a general circulation model for Titan, we demonstrate that annular modes are prominent in the atmospheres of both worlds, capturing a larger fraction of their respective variabilities than Earth’s. One mode describes latitudinal shifts of the jet on Mars, as on Earth, and vertical shifts of the jet on Titan. Another describes pulses of mid-latitude eddy kinetic energy on all three worlds, albeit with somewhat different characteristics. We demonstrate that this latter mode has predictive power for regional dust activity on Mars, revealing its usefulness for understanding Martian weather. The similarity of annular variability in dynamically diverse worlds suggests its ubiquity across the Solar System, potentially extending to exoplanets.

Annular modes arise from the internal dynamics of the atmosphere. In Earth’s atmosphere, they explain much of the weekly to monthly variability of the jet stream, synoptic wave activity and precipitation, and are therefore vital for understanding and predicting weather patterns. They are linked to the position and strength of the jet stream and atmospheric storm track. Modes are ‘annular’ if the variability they represent is zonally symmetric, that is, if changes occur in tandem along whole latitude circles. Two types of annular modes exist within the atmosphere of Earth. The first mode arises as north–south vacillations (quantified as the first empirical orthogonal function (EOF); see Methods) in the anomalous surface pressure or zonal-mean zonal wind. This mode appears independently in both the Northern and Southern hemispheres, in each case explaining 20–30% of the variance in the zonal-mean wind, geopotential height and surface pressure. The mode physically represents shifts in atmospheric mass between the polar regions and the middle latitudes. (The second EOF of the mode physically represents shifts in atmospheric mass between the polar regions and the middle latitudes.)

Mars inhabits a different regime of atmospheric dynamics, with a high Rossby number (although near-surface baroclinic waves occur in simulations of Titan’s atmosphere). Motivated by the possibility that annular modes may help diagnose and predict weather on other planets as they do for Earth, we investigate whether annular modes (including baroclinic modes) are present on Mars and Titan. This would indicate their ubiquity in terrestrial atmospheres and reveal an important common source of atmospheric variability for consideration on both Solar System planets and extrasolar planets.

The reported minimal influence of barotropic annular modes on Mars belied issues with the horizontal weighting of the analysed fields (Methods). The seemingly minor change to the weighting has enormous impacts on the resulting importance of annular modes on Mars. Using EOF analysis with the correct weighting, we identify both baroclinic and barotropic annular modes on Mars and Titan and also compare them to Earth’s modes. For Mars, we focus on each hemisphere’s fall and winter seasons and analyse two reanalyses of orbiter observations, the Mars Analysis Correction Data Assimilation (MACDA) and the Ensemble Mars Atmosphere Reanalysis System (EMARS). For Titan, we evaluate the full year using simulations from the Titan Atmosphere Model (TAM).

Martian annular mode in zonal wind

Our EOF analysis of the atmosphere of Mars (Methods) demonstrates many annular features reminiscent of those on Earth. Much of the large-scale variability during fall and winter (Ls = 180–370° for the northern hemisphere and Ls = 10–190° for the southern hemisphere; Ls is the areocentric longitude, see Methods) of the atmospheric flow at mid to high latitude is explained by an annular mode in the zonal-mean zonal wind (U-AM) (Fig. 1a–d and Extended Data Fig. 1a–d). This mode is the equivalent of Earth’s barotropic annular mode (Fig. 3 of ref. 4, Fig. 2a of ref. 6 and Fig. 2a of refs. 8,14). Two spatial structures dominate the variability of Mars’s zonal-mean zonal wind. A dipolar structure in latitude, which is equivalent to Earth’s U-AM, straddles the region of strongest winds (annual-mean zonal wind contoured in Fig. 1a–d) and explains the most variance in the northern hemisphere (~30–40%, Fig. 1b,d). As on Earth, the dipolar pattern represents latitudinal shifts of the jet. Because topography in the southern hemisphere varies greatly with latitude on Mars, such north–south shifts are disrupted. Additional spatial structures are also important in that hemisphere: a mono-polar structure, with a single centre of action, accounts for slightly more variance (~25–35%, Extended Data Fig. 1a,c) than the dipolar structure (~20–30%, Fig. 1a,c), indicating that both are similarly important. Regardless, the spatial locations of the dipolar modes (Fig. 1a–d) align in both hemispheres and across datasets.
The dipolar U-AM behaves like Earth’s U-AM, which links to eddy momentum fluxes and lacks any tilt in the vertical—a barotropic spatial structure. This inter-planetary similarity of the barotropic mode is revealed by regressing the eddy momentum fluxes onto the U-AM at a −1 day lag (Fig. 1i–l). Convergence of eddy momentum fluxes onto the U-AM at a barotropic mode is revealed by regressing the eddy momentum fluxes at −1 day lag (shading). Only regressions exceeding 99% confidence are shown.

The former can be defined in either the surface pressure or the zonal-mean wind (Extended Data Fig. 3b). Both structures equally reflect the movement of mass away from the pole at times of westerly anomalies (as is done for Fig. 1) and then regress back onto the surface pressure found when we first define the U-AM from zonal-mean zonal wind (Fig. 6 of ref. 10). Comparison of the U-AM from the surface pressure yields similar results for Mars as well. Calculation of the U-AM from the daily-mean surface pressure, with the correct weighting (Methods), duplicates the annular structure (Extended Data Fig. 2a) found when we first define the U-AM from zonal-mean zonal wind (as is done for Fig. 1) and then regress back onto the surface pressure (Extended Data Fig. 3b). Both structures equally reflect the movement of mass away from the pole at times of westerly anomalies with positive centres at 70° N/S and negative centres at approximately 40° N/S, all at around 100 Pa (approximately 20 km altitude), indicating that the spatial pattern is robust.

Like Earth’s barotropic mode, Mars’s U-AM is truly annular. The former can be defined in either the surface pressure or the zonal-mean zonal wind (Fig. 6 of ref. 10). Comparison of the U-AM calculated using either the zonal-mean wind or the surface pressure yields similar results for Mars as well. Calculation of the U-AM from the daily-mean surface pressure, with the correct weighting (Methods), duplicates the annular structure (Extended Data Fig. 2a) found when we first define the U-AM from zonal-mean zonal wind (as is done for Fig. 1) and then regress back onto the surface pressure (Extended Data Fig. 3b). Both structures equally reflect the movement of mass away from the pole at times of westerly anomalies.
Martian annular mode in eddy kinetic energy

In addition to the U-AM, we identify an annular mode in the zonal-mean EKE (EKE-AM) on Mars (Fig. 2a–d). Just as the U-AM resembles Earth’s barotropic mode, the newly identified Martian EKE-AM resembles Earth’s baroclinic annular mode (Fig. 2f of ref. 11 and Fig. 1 of ref. 15). The first spatial pattern is a single monopole that overlaps the greatest EKE and explains between 48% and 65% of the EKE variance during fall and winter (Fig. 2a–d), which is far larger than for Earth11,14. The location of the regressed zonal-mean EKE matches that of Earth’s baroclinic mode, but the magnitude of the EKE-AM is approximately double. The annular feature achieves a maximum at 60–70° N/S and 10–150 Pa, and is robust across both hemispheres and both datasets. Given the large degree of importance that Earth’s mode has in explaining extratropical wave activity, the comparatively larger percentage of variance explained by the EKE-AM points to its large influence in determining wave activity, and therefore dust events33, on Mars.

The EKE-AM links to poleward eddy heat fluxes that vary vertically (Fig. 2e–h), which matches the behaviour of Earth’s baroclinic mode and demonstrates that the EKE-AM represents (baroclinic) instabilities that instigate the type of travelling waves that initiate large dust events33. The relationship between eddy heat fluxes and the EKE-AM holds across hemispheres and datasets except for the southern-hemisphere MACDA domain, in which fluxes are weaker. Nevertheless, each domain exhibits a peak in the magnitude of eddy heat fluxes near the surface at the mid-latitudes, with a secondary peak around 100 Pa slanted poleward and passing through the maximum of the EKE (Fig. 2e–h, contours).

Earth’s baroclinic and barotropic annular modes are decoupled, meaning that there is essentially no correlation between them; they act independently of one another. In addition, Earth’s mode in EKE is not linked to eddy fluxes of momentum, and Earth’s mode in zonal wind is not linked to eddy fluxes of heat11,14. The Martian U-AM follows this pattern, as it does not regress strongly on either eddy heat fluxes or EKE (Fig. 1e–h). However, this is not the case for the Martian EKE-AM. The EKE-AM is associated with eddy fluxes of...
remarkably reminiscent of Earth’s EKE-AM, which also pinpoints annular structure, with longitudinal localization in storm tracks, is for mid-latitude weather on Mars. Therefore suggests that the EKE-AM may be an essential component upstream of Acidalia, Arcadia and Utopia Planitiae, which is a measure of the intensity of all waves, regressed on the zonal-mean zonal wind (Fig. 2i–l, contours). This is distinctly different from Earth’s EKE-AM, thus, the Martian EKE-AM cannot be established as strictly a baroclinic mode. The entangled nature of Martian annular modes corroborates wave analyses that find that transient eddies grow barotropically as well as baroclinically, depending on the period of the dominant waves. Thus, whereas annular modes on Mars are quite similar to those of Earth, the unique conditions of Mars provide some intriguing differences that demand continued investigation.

The connections between the EKE-AM and dust storm-producing travelling waves on Mars are corroborated by comparing the storm tracks on Mars to the EKE-AM. The mass-integrated EKE, which is a measure of the intensity of all waves, regressed on the EKE-AM peaks at 45–75° N and 15–60° S (Fig. 3c,d). It connects to the EKE-AM upstream of Acidalia, Arcadia and Utopia Planitiae in the northern hemisphere and near Argyre and Hellas Basins in the southern hemisphere, with only minor disagreements in magnitude between datasets (Extended Data Fig. 3e–h). Indeed, each of these regions hosts areas of increased storm activity from transient waves, yet reflect the amplification of waves in localized regions, because waves circumnavigate the globe. Furthermore, the clear annular structure, with longitudinal localization in storm tracks, is remarkably reminiscent of Earth's EKE-AM, which also pinpoints the Pacific, Atlantic and Southern Ocean storm tracks (Fig. 3a,b). The similarity in the annular modes in EKE on both Earth and Mars therefore suggests that the EKE-AM may be an essential component for mid-latitude weather on Mars.

**Impact of Martian annular modes on dust activity**

Earth’s annular modes link to observable and impactful atmospheric features such as precipitation, further implying that the newfound EKE-AM might be expected to impact observable Martian weather such as dust activity. To probe the link between the northern hemisphere EKE-AM and dust activity, we regress the EKE-AM onto the Mars Dust Activity Database for the dusty season of one Mars year. Regions where northern hemisphere dust storms initiate, including Acidalia, Arcadia and Utopia Planitiae, are highlighted when dust activity leads the EKE-AM in the regression (Fig. 4a), demonstrating a relationship between the mode and observable, impactful surface conditions on Mars. That the EKE-AM pinpoints regions related to dust storm activity in an independent dataset also increases the confidence that annular modes on Mars truly exist. In these three regions in the northern hemisphere, which are dust-lifting regions, dust activity peaks before the EKE-AM, meaning that dust is lifted by atmospheric waves before the EKE-AM reaches peak intensity. This is analogous to the relationship between Earth’s EKE-AM and precipitation, where precipitation peaks one day before waves do.

A key difference between precipitation on Earth and dust on Mars is that the latter remains lofted for weeks after initially being lifted. Thus, with Mars, the impact of the EKE-AM can remain long after the peak of the EKE itself. In fact, when the dust activity lags the EKE-AM (that is, the EKE-AM peak precedes the dust), locations into which northern hemisphere dust storms evolve, or flush, link positively to the northern EKE-AM (Fig. 4b). This relationship between the northern EKE-AM and southern hemisphere dust activity maximizes near 0.12 storms per sol between Argyre and Hellas Basins, which is the region into which most dust storms travel. Therefore, the leading behaviour of the EKE-AM for...
activity that moves from the north to the south indicates predictive abilities of annular modes for dust storms. Only those dust events that flush into the southern mid-latitudes become large enough to impact the surrounding atmosphere on regional and larger scales, so the EKE-AM could indicate when large dust events are favoured before they occur. These sorts of predictions could be vital, for example, for ensuring the safety of future crewed missions to Mars.

**Titan's annular modes**

We have shown that Earth and Mars share similar annular modes in zonal wind and EKE, which could be due to their similarity in dynamical regime. To test this, we now investigate annular modes on Titan, which presents a previously unexplored dynamical regime from the perspective of annular variability. With key differences from Earth and Mars, Titan, too, supports annular modes of variability in zonal-mean zonal wind and EKE, based on simulations with a Titan general circulation model (no reanalysis exists yet for Titan; see Methods). Although they potentially inaugurate additional research into Titan's atmospheric variability, these analyses should be interpreted with caution because they are from a single, albeit well-validated, model. Nevertheless, evidence of annular modes on Titan, in addition to Earth and Mars, points to the ubiquity of annular variability across the Solar System, which may hold notable promise for understanding atmospheric behaviour across worlds.

The U-AM in our Titan simulations is dipolar but with the opposing poles stacked vertically (Fig. 5a,b) instead of horizontally as on Earth or Mars. Titan's U-AM explains ~68% of the variance of the zonal-mean zonal wind, which is far more than for Earth or Mars. The negative pole resides at 300 hPa (approximately 30 km altitude), whereas the weaker positive pole resides near the lowest vertical extent of the jet. This spatial structure represents vertical oscillations of the jet, as opposed to the horizontal vacillations of the terrestrial and Martian U-AM. Titan's U-AM is characterized by co-located zonal wind and poleward momentum fluxes (Fig. 5i,j). There is little relationship between the U-AM and EKE, but the U-AM is associated with poleward heat fluxes near the surface and equatorward heat fluxes at the mid-levels (Fig. 5e,f). Despite the vertical alignment of the U-AM dipole, the mode is associated with low surface pressures at the pole and an annular feature between 30° and 45° N/S in the anomalous mass-integrated EKE (not shown), which may indicate that the waves associated with the EKE have barotropic components, in agreement with expectations for Titan's dynamical regime. This is counter to the nature of the terrestrial and Martian U-AM.

Titan's EKE-AM, although similar to Mars's and Earth's modes, also provides intriguing differences. Titan's EKE-AM explains 38.5 and 52% of the southern and northern hemisphere variances, respectively, in the zonal-mean EKE and has a single centre of action at 500 hPa and 60° N/S (Fig. 5c,d). However, this mode exhibits a vertically stacked dipole of eddy heat fluxes that are poleward at high
Altimetries and equatorward at the mid-levels. These equatorward eddy heat fluxes indicate that the waves generating the EKE cannot be baroclinic at the mid-levels of the atmosphere\(^4\). In addition, the EKE-AM regresses only weakly on the zonal wind (Fig. 5k,l, contours), similar to Earth's baroclinic mode, but links strongly to eddy momentum fluxes (Fig. 5k,l), like the Martian EKE-AM (Fig. 2). Titan's annular modes, therefore, share characteristics of both Earth's and Mars's modes. Whether they too have predictive power for weather on Titan remains to be explored.

Implications and perspectives

Previous studies suggested that annular variability might be unimportant in the atmosphere of Mars\(^6,7\); however, we find that annular variability is even more important on Mars than it is on Earth. The northern and southern Martian modes explain larger percentages of variance in the zonal wind than Earth's U-AM (Fig. 1). In addition, we identify a baroclinic annular mode in the EKE on Mars (Fig. 2). Titan's EKE-AM controls EKE throughout an annulus between 35° and 65° N/S, and activity is most strongly indicated in the northern hemisphere between 180° and 300° E (Fig. 3c,d), suggesting that there may be preferred locations for eddy activity as on Earth and Mars. In addition to longitudinal localization of the storm tracks for Earth and Mars, mass-integrated EKE is dramatically amplified throughout the mid-latitudes on all three worlds (Fig. 3).

An exciting application lies in the use of annular dynamics to explain observable phenomena on Mars, Titan and elsewhere. Annular modes on Earth link to the distribution of precipitation and climatology. Mars's modes are more similar to Earth's, but the possible modes of Titan demonstrate how the influence of differing planetary parameters modifies the atmospheric dynamics. Annular structure in the EKE-AM occurs on Earth, Mars and Titan between 35° and 65° N/S as seen in mass-integrated EKE (Fig. 3). These six fields are strikingly similar given the disparate geographies, storm tracks and—particularly for Titan—dynamical regimes of the three worlds. Mars's EKE-AM amplifies within the three northern\(^2,14,16\) and two southern\(^2,35\) storm tracks that generate dust activity (Fig. 3c,d). Titan's EKE-AM controls EKE throughout an annulus between 35° and 60° N/S, and activity is most strongly indicated in the northern hemisphere between 180° and 300° E (Fig. 3c,d), suggesting that there may be preferred locations for eddy activity as on Earth and Mars. In addition to longitudinal localization of the storm tracks for Earth and Mars, mass-integrated EKE is dramatically amplified throughout the mid-latitudes on all three worlds (Fig. 3).

Previous studies suggested that annular variability might be unimportant in the atmosphere of Mars\(^6,7\); however, we find that annular variability is even more important on Mars than it is on Earth. The northern and southern Martian modes explain larger percentages of variance in the zonal wind than Earth's U-AM (Fig. 1). In addition, we identify a baroclinic annular mode in the EKE on Mars (Fig. 2) and on Titan (Fig. 5) as well, both of which explain almost double the amount of variance in EKE, and thus wave activity, compared to Earth's baroclinic mode.

That Mars and Titan both exemplify annular variability opens a new window for comparative planetology and climatology. Mars's modes are more similar to Earth's, but the possible modes of Titan demonstrate how the influence of differing planetary parameters modifies the atmospheric dynamics. Annular structure in the

Fig. 5 | Zonal-mean structure of the annular modes in zonal-mean zonal wind and eddy kinetic energy on Titan. a,b, Dataset-averaged zonal-mean zonal wind (contours every 5 m s\(^{-1}\)) and regression of the U-AM onto the zonal-mean wind (shading). c,d, Dataset-averaged zonal-mean eddy kinetic energy (contours every 5 \(10^{-2} \text{ m}^2\text{s}^{-1}\)) and regression of the EKE-AM onto the zonal-mean eddy kinetic energy (shading). The individual column titles give the percentage of variance explained. e-h, Regressions onto the anomalous zonal-mean zonal wind and eddy kinetic energy (contours every 2.5 \(10^{-2} \text{ m}^2\text{s}^{-1}\)) and the anomalous eddy heat flux at 0 day lag (shading). i-l, Regressions onto the anomalous zonal-mean zonal wind (contours every 5 \(10^{-2} \text{ m}^2\text{s}^{-1}\)) and anomalous eddy momentum flux at –1 day lag for the U-AM (i,j) and for the EKE-AM (k,l). Only regressions exceeding 99% confidence are shown.

\(i\) Vol 5 | November 2021 | 1139–1147 | www.nature.com/natureastronomy

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by sublimation or deposition of the CO₂, seasonal ice cap. For Titan, annular modes may play a role in the sporadic nature of convective events41, but further observations and improved model simulations will be required to assess their relationship.

Finally, the existence of annular modes in atmospheres other than Earth’s proves the ubiquity of annular modes of variability across planetary atmospheres and demands a search for these modes beyond Mars and Titan. For example, Venus exhibits annularity in the ‘cold collar’ of temperatures surrounding the pole42; this may link to annular variability as Earth’s annular modes link to low temperatures4. Given this ubiquity, annular variability might be expected in gas and ice giants as well, for instance given the likely importance of eddies in driving Jupiter’s jets43. Annular modes might also impart intrinsic variability that sets the noise floor for detections of exoplanet winds via Doppler shifts45 so should be understood in that context. Each of these possibilities opens a promising avenue of research towards understanding how annular dynamics control observable variability in the atmospheres of Earth and other planets.

Methods

We perform an empirical orthogonal function analysis of annular structures of variability in the atmosphere of Mars using two reanalysis datasets, the MACDA43 and the EMARS. The latter consists of two eras, during which Thermal Emission Spectrometer data and Mars Climate Sounder data, respectively, are assimilated44. We conduct a similar analysis for Titan using a 20-Titan-year-long simulation of the TAM54. We use the ERA-Interim reanalysis for Earth data46.

Time of year on Mars. Timekeeping on Mars is related to the position of the planet in its orbit. The seasons on Mars are delineated using the aerocentric longitude, \( L_\text{a} \), which has a range of \( L_\text{a} = 0° - 360° \). For the northern hemisphere, vernal equinox is \( L_\text{a} = 0° \), summer solstice is \( L_\text{a} = 90° \), autumnal equinox is \( L_\text{a} = 180° \) and winter solstice is \( L_\text{a} = 270° \).

Mars reanalysis datasets. MACDA (v1.0)43 is a reanalysis of Thermal Emission Spectrometer retrievals from the Mars Global Surveyor during the period \( L_\text{a} = 141° \) Mars Year (MY) 24 to \( L_\text{a} = 86° \) MY 27. Thermal profiles up to 40 km twice per sol and total dust opacities once per sol are assimilated into the UK version of the Mars Global Circulation Model of the Laboratoire de Météorologie Dynamique47 using an analysis correction scheme48. MACDA uses a 5° x 5° horizontal grid with 25 sigma levels every two Mars hours.

EMARS (v1.0)49 includes Thermal Emission Spectrometer data, as well as assimilations from the Mars Climate Sounder48 onboard the Mars Reconnaissance Orbiter; thus, EMARS spans from \( L_\text{a} = 102° \) MY 24 to \( L_\text{a} = 102° \) MY 27 using the Thermal Emission Spectrometer, and spans from \( L_\text{a} = 112° \) MY 28 to \( L_\text{a} = 105° \) MY 33 using the Mars Climate Sounder48. EMARS is provided at 6° longitude x 5° latitude horizontal resolution with 28 hybrid sigma–pressure levels. EMARS uses a local ensemble transform Kalman filter to assimilate observations50.

EMARS is an ensemble dataset, meaning that the model is run multiple times with different parameterizations to characterize the ‘true’ synoptic state of the atmosphere as observed. Thus, the ensemble mean is used for the analysis. We favour the use of the ensemble mean rather than the use of an individual member because we seek to understand the most likely state of the atmosphere rather than obtain a deterministic diagnosis from one model. For the Thermal Emission Spectrometer era, the ensemble has been shown to generally converge to a single solution when analysing transient waves, but for Mars Climate Sounder data, surface features are less constrained51. Nevertheless, repetition of our analysis on a single ensemble member from EMARS does not change our results (not shown).

Titan atmospheric model. Although Mars research has benefited from semi-continuous and regular observations of its atmosphere over several Martian years, Titan’s long year and relative distance have prevented continuous monitoring for any substantial length of time. The recent Cassini mission only sporadically observed Titan during its tour of the Saturn system, which covered half of a Titan year. Given this relative dearth of observational data and a lack of reanalysis products for Titan, the next best option is an observationally benchmarked general circulation model.

Therefore, to explore the possibility of annular modes on Titan, we turn to an analysis of simulations of Titan’s atmosphere with TAM52. A 20 Titan-year dataset is re-initialized from a previously reported TAM simulation52 (which includes the atmospheric model coupled to a land model incorporating interactive hydrology) using the preferred version with a surface hydraulic conductivity of \( k = 5 \times 10^{-11} \text{m}^2 \text{s}^{-1} \) as well as a tuned convective parameterization53, which matches best to observations of the hydrologic cycle. TAM has been thoroughly vetted against numerous observations of Titan, and its simulated circulation has been shown to be robust52,53,54 as well as favourably comparable to other models’ simulations of Titan’s climate52,54. Nevertheless, the Titan analyses described here are of a single model, so should be interpreted with caution.

Empirical orthogonal function analysis. Earth’s annular modes are diagnosed using EOF analysis55,56. We adopt a similar methodology for Mars and Titan to identify the leading patterns of annular climatic variability. EOF analysis decomposes multiple time series of functions (of orthogonal dimensions as the analysed dataset) that are determined by statistical relationships within the dataset. EOFs are the eigenvectors of the covariance matrix at each grid point and time step. The eigenvalue associated with each EOF eigenvector corresponds to the variance that is accounted for by the EOF. These functions are orthogonal, meaning that they most efficiently represent the variance of the entire dataset paired with a principal component (of the same length as the original dataset). This principal component describes the temporal evolution or amplitude of the EOF at every time step of the dataset. The EOFs and associated principal components are ordered such that the first EOF explains the largest amount of variance of the original field; each subsequent EOF explains the largest amount of remaining variance57.

The EOFs shown in the analysis are tested for significance, which is defined as their being well separated from adjacent modes58. This is estimated using the formula \( \lambda_n \approx 2(N-1)/N \), where \( N \) is the number of time steps and \( \lambda_n \) is the eigenvalue for each mode. For all reanalysis domains for Mars and for the TAM simulation, all first modes are well separated from the second modes, and all second modes are well separated from the third modes.

The U-AM mode is defined using the zonal-mean zonal wind [\( u \)], and the EKE-AM is independently defined using the zonal-mean eddy kinetic energy [\( \text{EKE} = \left[u^2 + v^2\right]/2 \)], where square brackets denote the zonal mean, asterisks indicate departures from the zonal mean and \( v \) is the meridional wind. The eddy meridional flux [\( v^* \)] and eddy meridional heat flux [\( v^* T^* \)] are also considered, where \( T \) is the temperature. Eddies and fluxes are calculated at each output time step within MACDA or EMARS and then averaged over each sol. Eddies and fluxes are calculated within TAM at each model time step (600 s) and averaged over an output frequency of approximately 0.9 Titan days.

For the Martian U-AM, we differentiate spatial structures as dipolar or non-dipolar modes. The non-dipolar U-AM on Mars (Extended Data Fig 1) explains marginally more variance in the southern hemisphere than the dipolar mode (Fig 1). The additional mode is tri-polar in MACDA (Extended Data Fig 1a,b), signifying splitting of the jet, and mono-polar in the southern hemisphere in EMARS (Extended Data Fig 1c), representing intensification of the jet. These variations in structure for both the first and second EOFs are not uncommon for Earth4,5 and may represent differences in the representation of the jet between reanalyses. The regressed momentum fluxes are co-located with a centre of regressed zonal wind (Extended Data Fig 1i–l). This does not correspond to a barotropic mode and is therefore not considered further.

Anomalies defined from the seasonal average. In most studies of Earth’s annular modes, EOF analysis is performed on anomalies that are defined by subtracting the seasonal cycle from each year. For this method to successfully approximate the real seasonal cycle, the dataset must be of a long enough duration that a single year with large anomalies does not influence the averaged yearly cycle. For Mars, and most other planets, derived from a single simulation, this is not the case. The EOFs shown in the analysis are tested for significance, which is defined as their being well separated from adjacent modes58. This is estimated using the formula \( \lambda_n \approx 2(N-1)/N \), where \( N \) is the number of time steps and \( \lambda_n \) is the eigenvalue for each mode. For all reanalysis domains for Mars and for the TAM simulation, all first modes are well separated from the second modes, and all second modes are well separated from the third modes.

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Sensitivity to domain size. For Mars, we analyse the daily mean of each variable over the domain 700°–1 Pa and 0°–90° N/S for the [\( u \)]. The EOF structure of the EKE-AM for Mars is robust as domain size is changed. The spatial structure of the Martian U-AM remains unchanged when the domain size is decreased; however, if the domain of analysis is increased to the equator, an additional mode is revealed within the EMARS datasets that represents strengthening and weakening of the retrograde jet at the equator, which for large portions of the year is stronger in EMARS than in MACDA43. For Titan, we analyse fields from the surface (around 1,450 Pa) to the top of the model domain at...
Weighting in the meridional direction. Before performing the EOF analysis, the Mars reanalysis data are converted to pressure coordinates in the vertical direction. All data are weighted by mass vertically and weighted in the meridional direction by a factor of $\sqrt{\cos \phi}$, where $\phi$ is the latitude. Previous efforts to describe annular variability in the atmosphere of Mars using the surface pressure, weighted by $\cos \phi$, demoted the annular modes of variability to the third EOF\cite{16}. The use of an inappropriate weighting ($\cos \phi$) in the meridional direction also relegates Earth’s barotropic annular mode in geopotential height to the third EOF, whereas weighting with $\sqrt{\cos \phi}$ places the annular mode as the leading EOF\cite{17}. Application of our EOF analysis of surface pressure from EMARS to incorrectly weighted ($\cos \phi$) anomalous, daily-mean surface pressure also shows the most prominent annular mode in the third EOF (Extended Data Fig. 2f), whereas the appropriately weighted ($\sqrt{\cos \phi}$), anomalous, daily-mean surface pressure from EMARS yields a regression map with an annular mode in EOF 1 (Extended Data Fig. 2a). The factor $\sqrt{\cos \phi}$ is used because variance, which is what is assessed in EOF analysis, is a squared quantity (see Extended Data Fig. 2a versus 2b).

One complexity for Mars is the deposition and sublimation of the CO2 ice cap, which breaks the relationship between the shift of the zonal wind maximum and mass: for the times of year when the CO2 ice cap is changing, atmospheric mass is not conserved. If the surface pressure can change independently of the jet (in this case because temperature changes control the increase or decrease of atmospheric mass and surface pressure), then annular structures in the jet need not necessarily equate to annular structures in the surface pressure. Indeed, the second spatial structure of the U-AM defined from the surface pressure is not annular (Extended Data Fig. 2b), despite the equivalent structure being annular when defined from the zonal-mean zonal wind (not shown). Thus, care must be taken when comparing the U-AM calculated from either the winds or the surface pressure.

Regression of principal components. The spatial patterns produced by EOF analysis indicate the locations of action of the annular modes but do not indicate the locations where the modes most impact the variables of interest. To ascertain these links, we regress the anomaly fields (of zonal wind, momentum flux, surface pressure, and so on) to the associated principal component to generate maps of the regression. The principal components are standardized by dividing each by its standard deviation. This is preferred because standardized principal component time series are unitless, so the regressed maps have the same units as the anomaly field itself\cite{18}. The resulting maps correspond to anomalies in the regressed field that are associated with variations in the principal component. We assess the significance of regression coefficients with the $t$ statistic. The number of degrees of freedom used in the test of significance is computed from the lag 1 autocorrelation\cite{19}. Throughout the work, the level of significance is noted in the text and figure captions, and results are never reported below the 95% confidence level.

For the U-AM on Titan, we regress the eddy momentum fluxes at a lag of $–1$ day. For the U-AM on Mars, we regress the eddy momentum and eddy heat fluxes at a lag of $–1$ sol, following terrestrial results\cite{20}. For the EKE-AM, we regress all fluxes for both Mars and Titan at a lag of zero, as the fluxes maximize coincident with the principal components.

For the Titan results, we regress the entire principal component time series onto each field of interest. For the Mars reanalysis datasets, we do not regress during the periods of global dust storms ($L_s = 170–300^\circ$ MY 25 and $L_s = 260–325^\circ$ MY 28), due to the large, transient impact on wind and temperature fields. To ensure that the annular modes themselves are not simply artefacts of the global dust storms, we have repeated our analyses excluding the global dust storms entirely. This yields five periods of comparison: before the MY 25 global dust event for MACDA and EMARS, after the MY 25 global dust event for MACDA and EMARS, and after the MY 28 global dust event for EMARS. Each of the EOFs and principal components for both annular modes are correlated to the full run of the analysis at $r \geq 0.95$. This implies that the global dust storms merely amplify the annular modes of variability themselves instead of imposing new patterns of variability.

Dust storms flush from the northern to the southern hemispheres during northern autumn and winter\cite{21}. Therefore, to prevent inter-hemispheric dynamics from impacting the interpretation of the annular modes, we present only results in which we regress the principal components for the northern hemisphere for the period $L_s = 180–370^\circ$ and the southern hemisphere for $L_s = 10–190^\circ$. These periods correspond to the times of the strongest transient wave activity in each hemisphere\cite{22}.

Mars dust activity database. Observations of Martian dust storm activity are taken from the Mars Dust Activity Database (MDAD)\cite{23}. Each Mars Daily Global Map from the Mars Color Imager covers 90° N to 90° S. The period $L_s = 180–360^\circ$, which is typically considered the dust storm season\cite{24}, from MY 31 is used.

The MDAD notes all dust storm activity with well-defined boundaries on Mars with area $>10^6$ km$^2$ and indicates each storm individually with an identification number. Dust storms with well-defined boundaries are easily identified from Mars Daily Global Maps, with the edges of the dust storms manually outlined\cite{25}. For comparison to the EKE-AM, the MDAD is re-binned from 0.1° x 0.1° resolution to 1° x 1° resolution, and all of the dust storms on each sol are collected together. The resulting array is regressed against the EKE-AM just as other fields taken directly from the reanalysis datasets.

Data availability

The Mars Analysis Correction Data Assimilation is available at https://catalogue.ceda.ac.uk/uuid/01c44f905fbede428e/bd57969a11177, The Ensemble Mars Atmospheric Reanalysis System is available at ftp://ftp.pasda.psu.edu/pub/commons/meteorology/greybush/emars-1p0/data/. ERA-Interim data are available at https://www.ecmwf.int. The Mars Dust Activity Database is available at https://doi.org/10.7910/DVN/FR2Z5. Titan Atmospheric Model results are archived on Zenodo at https://doi.org/10.5281/zenodo.4780576.

Code availability

The source code for TAM is currently not publicly available. EO analysis was done in part with the Climate Data Toolbox for MATLAB (https://github.com/chadagnee/CDT). Scripts used in the generation of figures can be obtained from the corresponding author upon request.

Received: 27 April 2020; Accepted: 9 July 2021; Published online: 30 August 2021.

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Author contributions J.M.B. conceived the work, J.M.B. performed the analysis and wrote the manuscript, with contributions from J.M.L. J.M.L. ran the TAM simulations.

Competing interests The authors declare no competing interests.

Additional information Extended data is available for this paper at https://doi.org/10.1038/s41550-021-01447-4.

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Peer review information *Nature Astronomy* thanks the anonymous reviewers for their contribution to the peer review of this work.

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Extended Data Fig. 1 | The spatial signature of the first non-dipolar annular mode in anomalous zonal-mean zonal wind on Mars for both reanalysis datasets. (a–l) As in Fig. 1, but for the first non-dipolar U-AM.
Extended Data Fig. 2 | Polar plots of the regression of the first three EOFs onto the anomalous surface pressure from EMARS in the northern hemisphere. (a, c, e) results performed using weighting of $\sqrt{\cos \phi}$. (b, d, f) results using $\cos \phi$. The individual panel titles indicate the percent of variance explained in each EOF. Topography is shown in 2000 m increments with the 0 m contour dot-dashed in gray and negative contours dashed. Regressions are only shown exceeding 99% confidence.
Extended Data Fig. 3 | Polar plots of the regression of the Martian U-AM onto the anomalous surface pressure (a–d) and the regression of the Martian EKE-AM onto the anomalous, vertically (mass) integrated EKE (e–h). (a, c, e, g) MACDA. (b, d, f, h) EMARS. Topography is shown in 2000 m increments with the 0 m contour dot-dashed in gray and negative contours dashed. Regressions are only shown exceeding 99% confidence.