THE ENSEMBLE MARS ATMOSPHERE REANALYSIS SYSTEM (EMARS): FEATURE-BASED EVALUATION OF TRANSIENT EDDIES

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Introduction: The Ensemble Mars Atmosphere Reanalysis System (EMARS) combines insights from spacecraft observations and model simulations using data assimilation, producing a comprehensive, multi-annual record of Martian weather and its uncertainties. Evaluation of reanalysis products should include both forecast-based [1] (e.g. short term forecasts minus observations; ensemble spread) and feature-based methods: an assessment of how realistically the reanalysis produces the zonal mean circulation, polar vortex [2], transient eddies, thermal tides [3], aerosol distributions, water and CO_2 cycles. In this abstract, we focus on transient eddies, also known as traveling waves, in the lower (below 300 Pa) atmosphere.

Data and Methodology:

EMARS assimilates observations from both the Thermal Emission Spectrometer (TES) [4] and Mars Climate Sounder (MCS) [5] instruments using the Local Ensemble Transform Kalman Filter (LETKF) [6] and the GFDL Mars Global Climate Model (MGCM). The resulting product contains hourly gridded fields of temperature, wind, surface pressure, and aerosols spanning over 6 Martian years, as well as their uncertainties as estimated by an ensemble of 16 members. Retrieved temperature observations are assimilated, and temperature, wind, and surface pressure are updated by the LETKF based on the error covariances estimated from the ensemble perturbations. Dust is advected in the model and adjusted in the boundary layer to correspond to the Montabone [7] dust product. The model simulations include radiatively active water ice clouds and topographic gravity wave drag.

Results:

Eddy Structure: Figure 1 shows a horizontal cross section through an EMARS lower atmosphere transient eddy during the TES period. A wave-3 structure is evident, with the wind, temperature, and pressure fields demonstrating approximately geostrophic balance. Wave regimes in the lower atmosphere tend to vary from wavenumber 1 to 3, with wave 3 typically linked to flushing dust storms.

Eddy Climatology and Wave Regimes: Figure 2 summarizes the strength and latitudinal extent of eddy activity in each hemisphere. Transient eddy activity typically lasts from Ls 170 to Ls 60 in the northern hemisphere, and Ls 0 to Ls 200-240 in the southern hemisphere. A solsticial pause is evident in the mid-winter of each. The TES and MCS years show systematic differences in the length of the SH eddy season; modeling studies have shown the strength and seasonality of eddies to be dependent upon aerosol distributions in the atmosphere [8]. Transient eddies in the lower atmosphere of Mars generally have a dominant zonal wavenumber regime between 1 and 3. We have systematically compared these regimes across all 6 years of EMARS (not shown), and found spring to be the most likely time for wave 3.

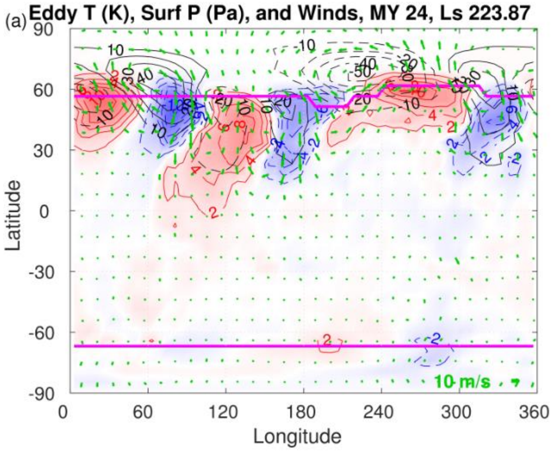

Figure 1: Synoptic maps depicting the eddy field for EMARS at the model sigma level ~1 km above the surface during (a) MY 24 Ls 224, which is during the TES era. Eddy temperatures (K; red / blue shading and contours for warm / cold anomalies), eddy pressures (Pa; solid black contours for positive values, dashed black contours for negative values), and eddy wind field (green arrows pointing in the direction the wind is blowing towards).

Convergence on a Synoptic State: A key question for Mars atmosphere reanalyses is whether they converge upon the correct synoptic state representing the actual weather patterns on Mars at a particular time. One advantage of ensemble-based techniques (such as the LETKF used in EMARS) is that an ensemble of plausible atmospheric states are provided. The spread of these ensemble members, when properly weighting the background and observation errors and adjusted using adaptive inflation, provides a metric of confidence or uncertainty in the representation of the state. Figure 3 shows a sample "postage stamp" plot of all 16 ensemble members, along with the ensemble mean, for TES EMARS. While they differ on fine-

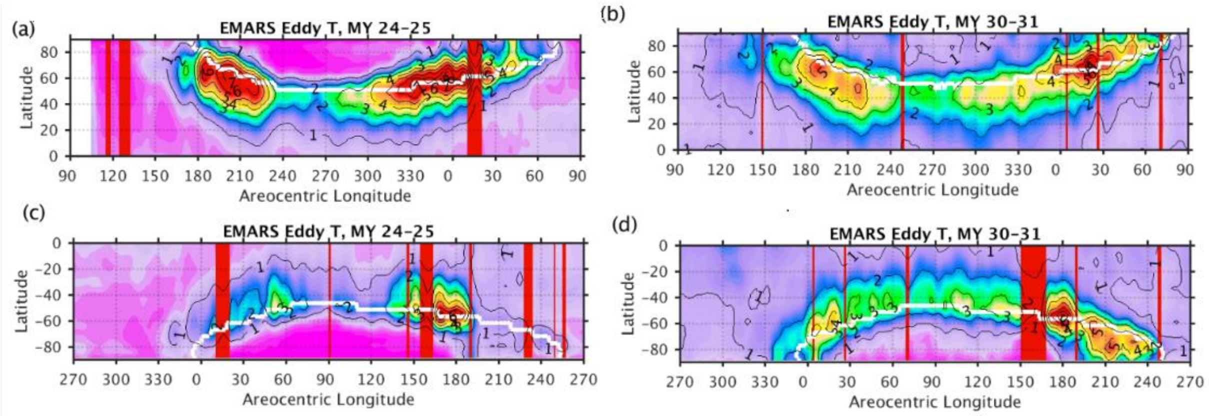

Figure 2: EMARS Northern (a, b) and Southern (c, d) Hemisphere Temperature eddy wave activity (RMS amplitude, K) for (a, c) MY 24-25 (TES era) and (b, d) MY 30-31 (MCS era) at the model sigma level ~1 km above the surface . Thick red bars over the plots indicate time periods when spacecraft observations were not available. White lines indicate modelled location of seasonal CO2 ice cap edge.

scale details, the general agreement of the wavenumber and phase indicates a convergence about a unique synoptic state. Whereas the TES ensemble mean eddy strength is similar to the individual members, the mean is weaker than the individual members for MCS. Similar ensemble plots for MCS EMARS show a lesser degree of convergence, indicating that the relative lack of observations in the lowest 5 km of the atmosphere provides a greater challenge for constraining the shallowest transient eddies.

Comparisons with Free Runs and MACDA: We have compared EMARS results to those from the Mars Analysis Correction Data Assimilation (MACDA) reanalysis version 1.0 [9] as well as underlying control runs (freely running model simulations) corresponding to each dataset. It is clear that transient eddies in EMARS and MACDA are more similar to one another than to their respective control runs. Synoptic maps (e.g. Fig 1) at specific times generally show a correspondence in wavenumber regime and phase between MACDA and EMARS, although the strength of the eddies and details of the circulation patterns exhibit some differences.

Comparison with Radio Science and Viking Lander: A wave with a ~2.3 sol period observed in the Viking lander data is also found in reanalysis time surface pressure series; this wave corresponds to a zonal wavenumber 3, which is associated with regional dust storms. We have also compared wave regimes in EMARS with those detected in radio science [10], with a high percentage correspondence.

References: [1] Greybush, S. J., et al. (2012), *J. Geophys. Res. Planets*, 117, E11008. [2] Waugh, D. W. et al. (2016), *J. Geophys. Res. Planets, 121,* 1770-1785. [3] Zhao et al. (2015), Tellus A, 67, 26042. [4] Smith, M. D. et al. (2001), *J. Geophys. Res.*, *106*, E10, 23929-23945. [5] McCleese, D. J. et al. (2007), *J. Geophys. Res.*, *112*, E05S06. [6] Hunt, B. R. et al. (2007), *Physica D*, *230*, 112-126 [7] Montabone, L. et al. (2015), *Icarus*, *251*, 65-95. [8] Mulholland, D. P. et al. (2016) *Icarus, 264, 467-477.* [9] Montabone, L. et al. (2014) Geoscience Data Journal, 1, 2, 129-139. [10] Hinson et al. (2012) *Icarus, 219, 307-320.*

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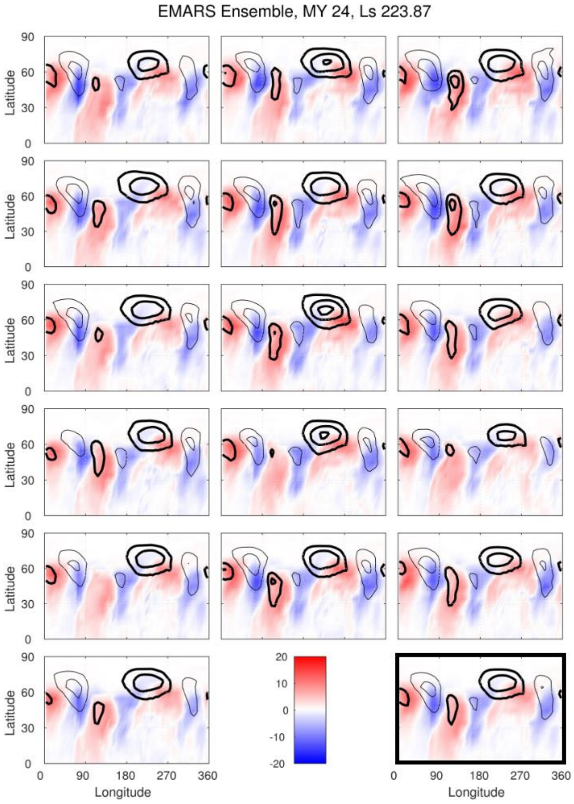

Figure 3: Synoptic maps of every ensemble member in EMARS while assimilating TES observations with the ensemble mean at bottom right. Temperature eddy amplitude [K] is shown in color. Pressure eddy amplitude is contoured at 20 Pa intervals, with low pressure bolded. Members have increasing dust downwards and increasing ice radiative forcing rightwards.