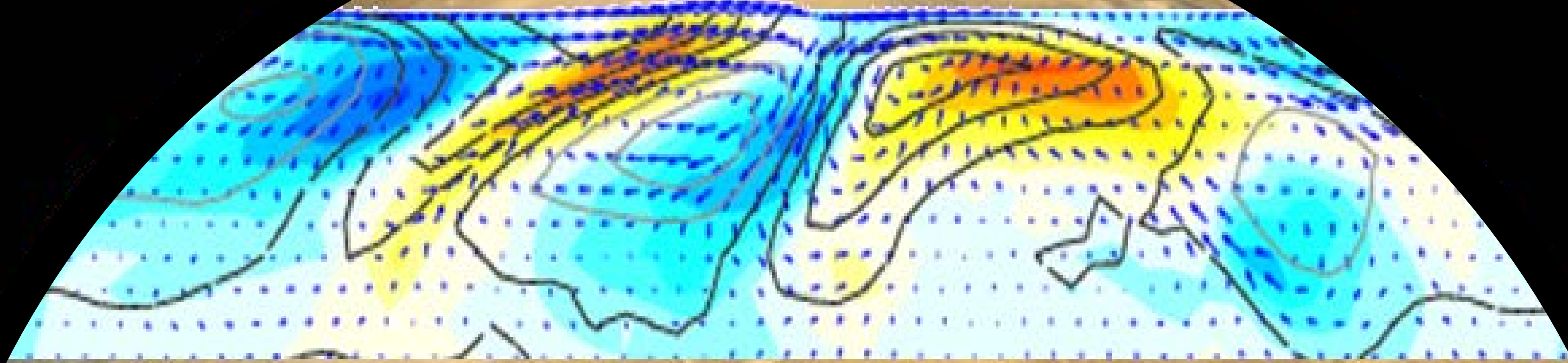

The Ensemble Mars Atmosphere Reanalysis System (EMARS): Feature-Based Evaluation of Transient Eddies

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Mars Atmosphere Data Assimilation Workshop

Le Bourget-du-Lac, France, August 29, 2018

EMARS: Ensemble Mars Atmosphere Reanalysis System

Data assimilation optimally combines spacecraft **observations** with short-term model **forecasts** to create **analyses**. Our reanalysis consists of the:

- TES and MCS temperature and aerosol retrievals.
- GFDL MGCM Mars Global Climate Model (MGCM).
- LETKF ensemble data assimilation system.

Reanalysis Product Contains:

- 3 years of TES, 3+ years of MCS analyses.
- Hourly fields of temperature, winds, surface pressure, aerosol.
- Atmospheric state and its uncertainty (ensemble means and spread).

RMetS Royal Meteorological Society
Geoscience Data Journal
Open Access

The Ensemble Mars Atmosphere Reanalysis System (EMARS) Dataset Version 1.0

Article and dataset in preparation for release to peer review, scheduled Fall 2018. Feedback welcome!

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The Ensemble Mars Atmosphere Reanalysis System (EMARS) dataset version 1.0 contains hourly gridded atmospheric variables for the planet Mars, spanning Mars Year (MY) 24 through 33 (1999 through 2017). A reanalysis represents the best estimate of the state of the atmosphere by combining observations that are sparse in space and time with a dynamical model and weighting them by their uncertainties. EMARS uses the Local Ensemble Transform Kalman Filter (LETKF) for data assimilation with the GFDL/NASA Mars Global Climate Model (MGCM). Observations that are assimilated include the Thermal Emission Spectrometer (TES) and Mars Climate Sounder (MCS) temperature retrievals. The dataset includes gridded fields of temperature, wind, surface pressure, as well as dust, water ice, CO_2 ice, and other atmospheric quantities. Reanalyses are useful for both science and engineering studies, including investigations of transient eddies, the polar vortex, thermal tides, and dust storms, and during spacecraft operations.

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Received: xxx, revised: xxx, accepted: xxx

Key words: Mars, Reanalysis, Ensemble, Assimilation, Atmosphere

Dataset

Details of the dataset(s) referred to in the paper. Include at least the name of dataset, data centre, and DOI or other unique identifier. Where possible please also provide the following details:
Identifier: xxxxx
Creator: The Pennsylvania State University, University of Maryland, AER, NASA
Title: Ensemble Mars Reanalysis System (EMARS) version 1.0
Publisher: Penn State Data Commons
Publication year: 2018
(Resource type): xxxxxxx
(Version): 1.0

Modeling and Assimilation Configuration

- **Ensemble Spread**: Adaptive Inflation; Varying Aerosols
- **Dust**: 3 Tracers advected by model, adjusted in boundary layer to match observed column opacities.
- **Water Ice Clouds**: radiatively active
- **CO2 Cycle**: mass conservation and supersaturation filter.
- Parameterizations: includes topographic gravity wave drag.
- Assimilation window of 1 hour.
- Adaptive inflation of ensemble spread.
- **Forward Model**: to be more consistent with observations, vertical weighting of model matches degrees of freedom in observations.

Note: parameter estimation (within ensemble data assimilation) can be used to further refine model configuration.

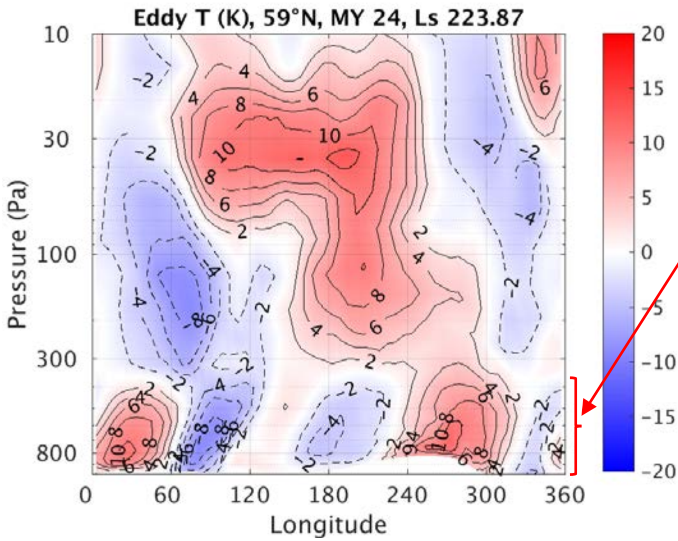
Feature-Based Verification: A Synergy of Investigating Mars Science and Innovating Assimilation Techniques

- Zonal Mean Circulation (Greybush et al., 2012)
  - Improving ensemble spread, aerosol spatial and temporal distributions, and empirical bias correction improve the zonal temperature distribution and RMSE.
- Thermal Tides (Zhao et al., 2015)
  - Using a shorter assimilation window avoids resonance and enables a better depiction of tide modes.
- Polar Vortex (Waugh et al., 2016)
  - Topographic wave drag and remote responses from aerosol heating shape the strength and configuration of the polar vortex.
- Atmospheric Aerosol (ongoing)
  - Exploring strategies for updating both temperature and aerosol fields can improve aerosol vertical structure and model heating rates.
- **Transient Eddies** (this presentation; Greybush et al., *Icarus*)

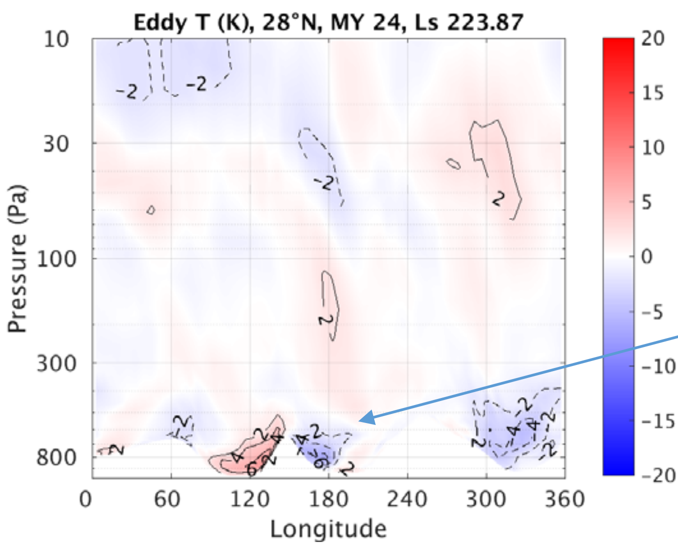
Transient Eddy Science Questions

- What is the seasonal and interannual variability of transient eddies / traveling waves in reanalyses?
  - Wave amplitude, wavenumber by season
  - Wave regimes
- Are characteristics of transient eddies in reanalyses different compared to freely running models?
  - Comparisons of both EMARS and MACDA and their control runs
- Can we converge on unique transient eddies in a reanalysis?
  - Robustness of traveling waves within EMARS; between EMARS and MACDA
  - Examine synoptic state and ensemble spread
- To what aspects of Mars atmosphere dynamics, observing system, and assimilation technique are wave systems sensitive?
  - How do MCS and TES reanalysis waves compare?
  - What is the impact of observation vertical resolution on waves?
- How do transient eddies compare to other independent observations?
  - EMARS vs. Viking and radio science wave characteristics

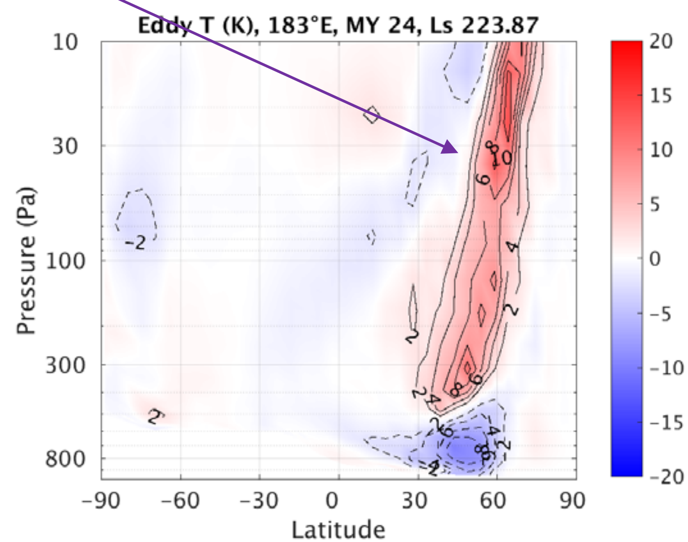
Vertical Cross Sections of Transient Eddies



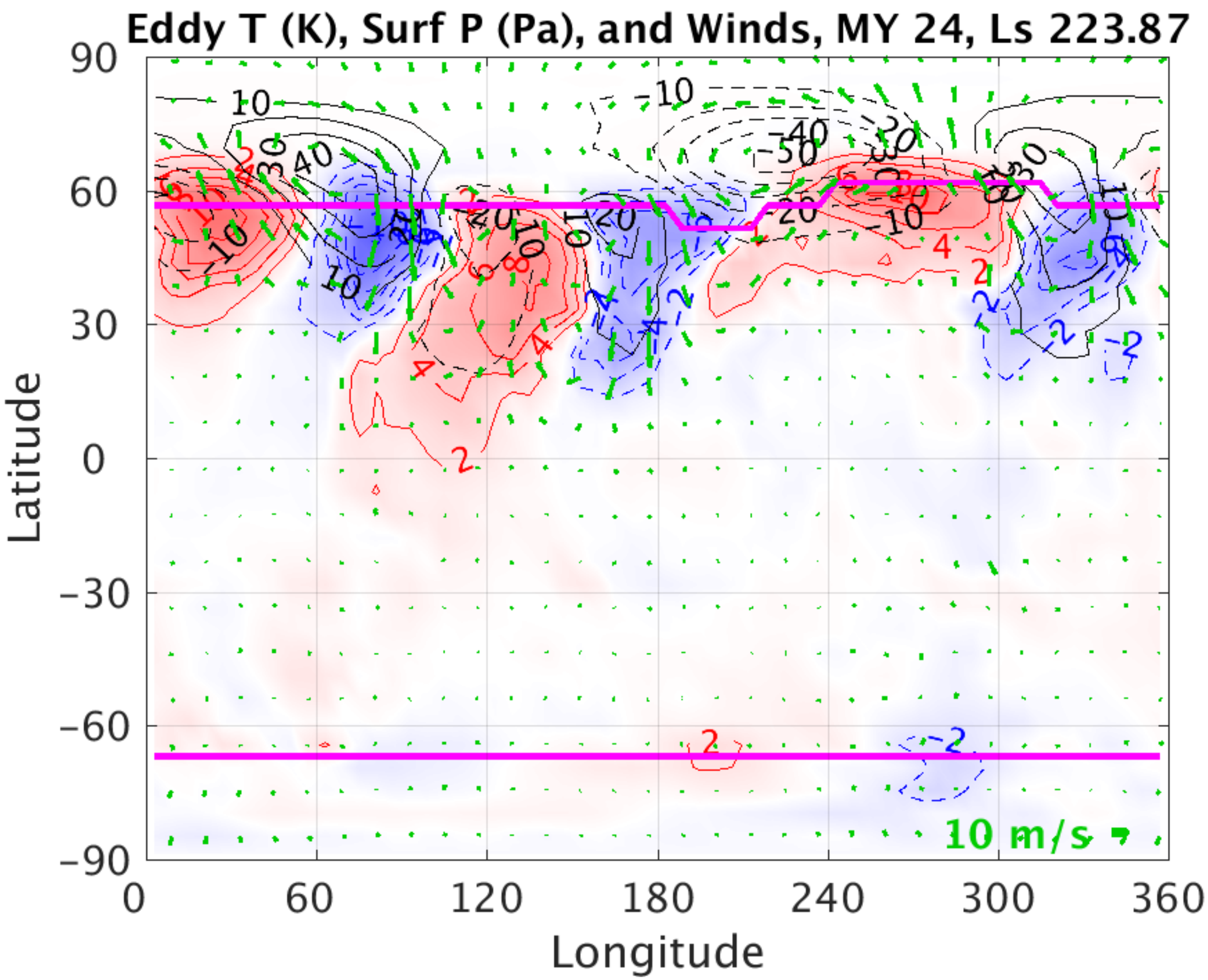
For this study we focus on low level (<10 km) eddies, as these eddies are relevant for dust lifting. Eddies also occur at higher altitudes along the polar vortex.

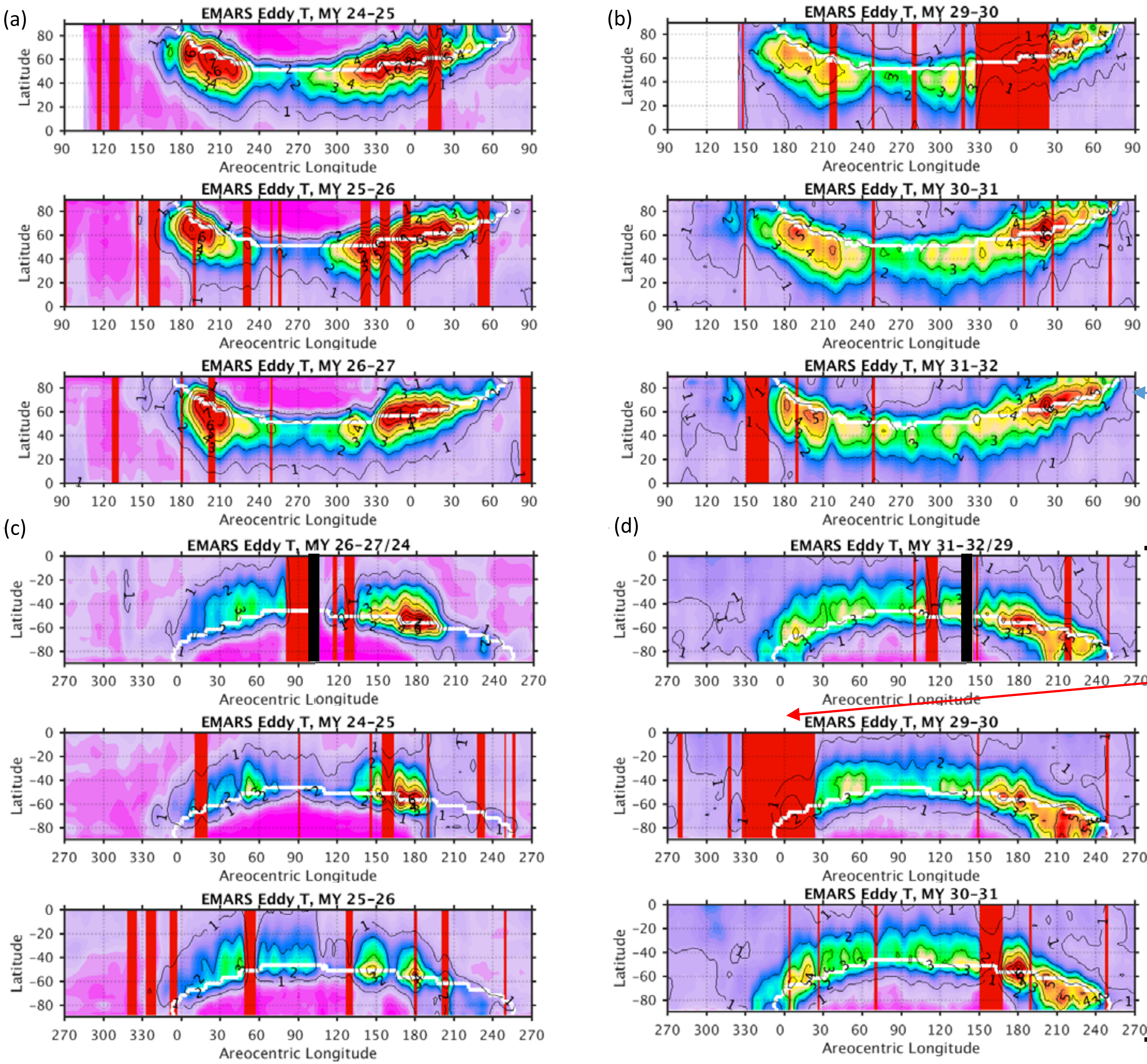


Shallow extent of Zonal Wave 3
(e.g. Mooring and Wilson, 2015)



Synoptic Map of EMARS Transient Eddy





EMARS Eddy Climatology

Ensemble Mean

Temperature RMS (K), ~1km above surface

NH

Ice Cap Edge: White Line

Missing Obs: Red Area

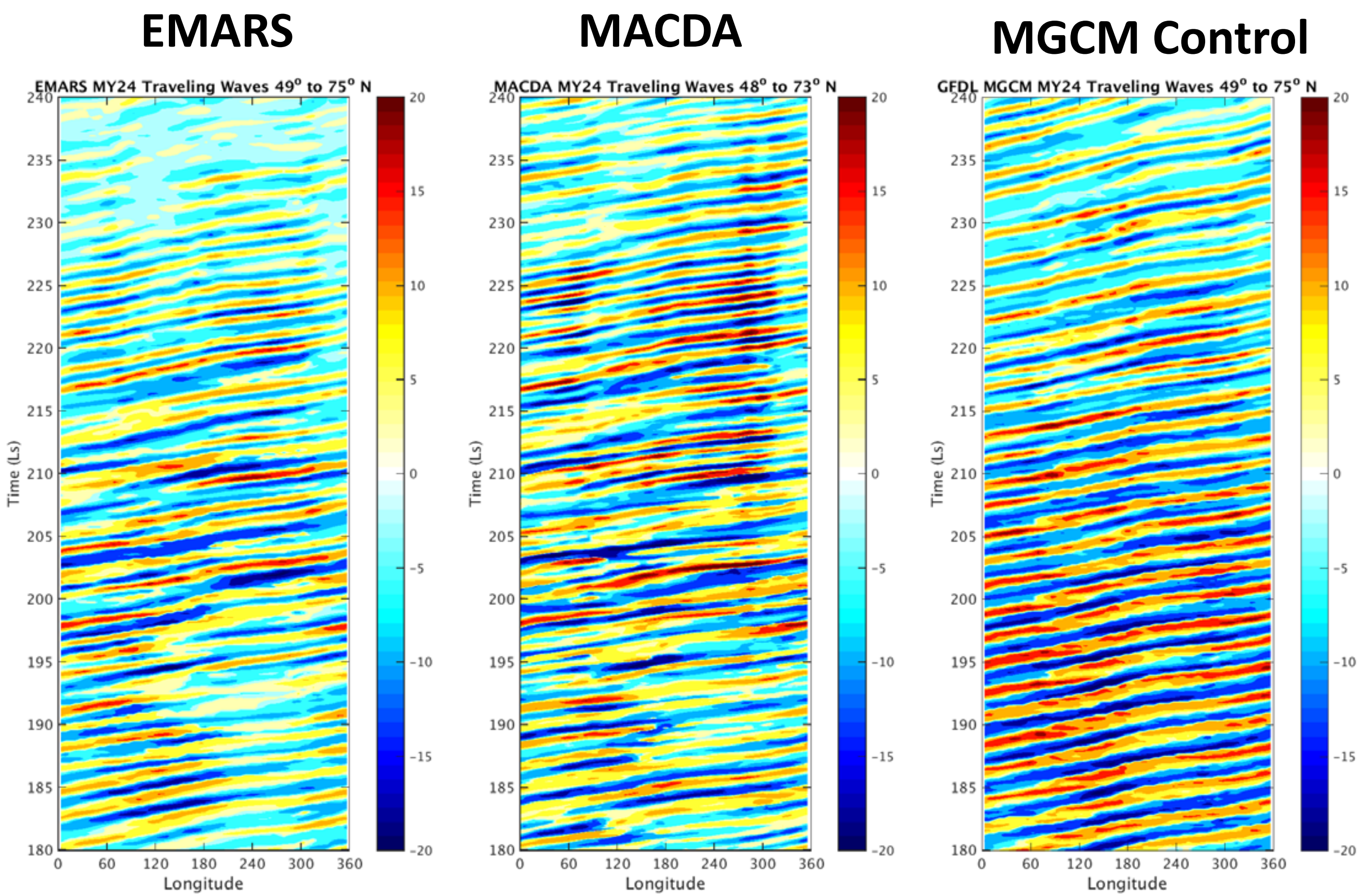
SH

General Similarities, Yet Some Systematic Differences:

Amplitudes between TES and MCS, SH seasonal extent

What is the seasonal and interannual variability of transient eddies / traveling waves in reanalyses?

Transient Eddy Hovmöller Diagrams

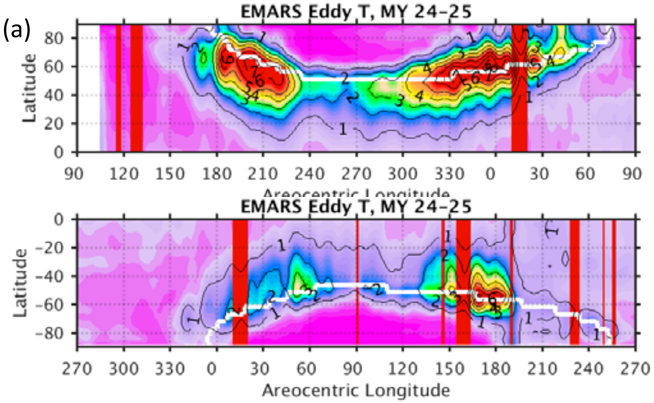


Are characteristics of traveling waves in reanalyses unique compared to freely running models? **Yes**

Reanalyses vs. Control Runs

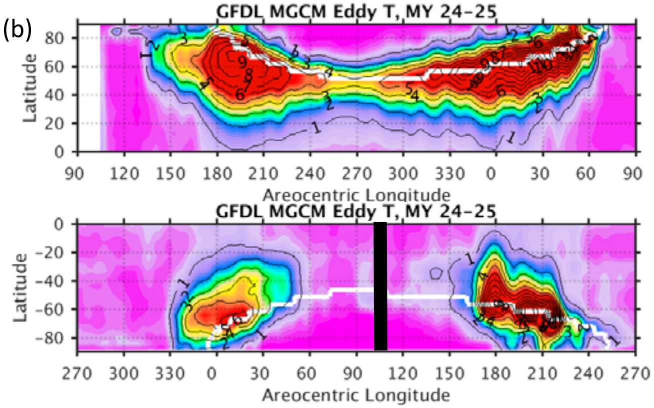
EMARS

(a)



EMARS Control

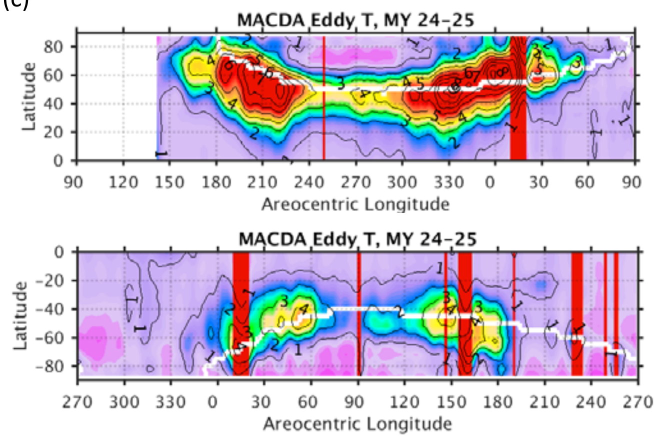
(b)



Traveling waves in EMARS vs. MACDA are more similar to each other than to the GCM control runs.

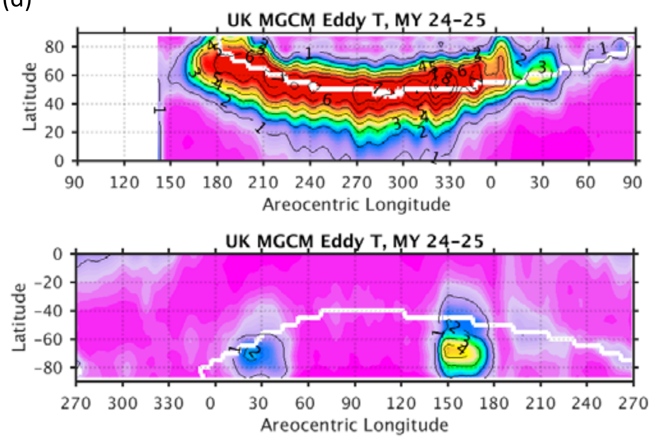
MACDA

(c)



MACDA Control

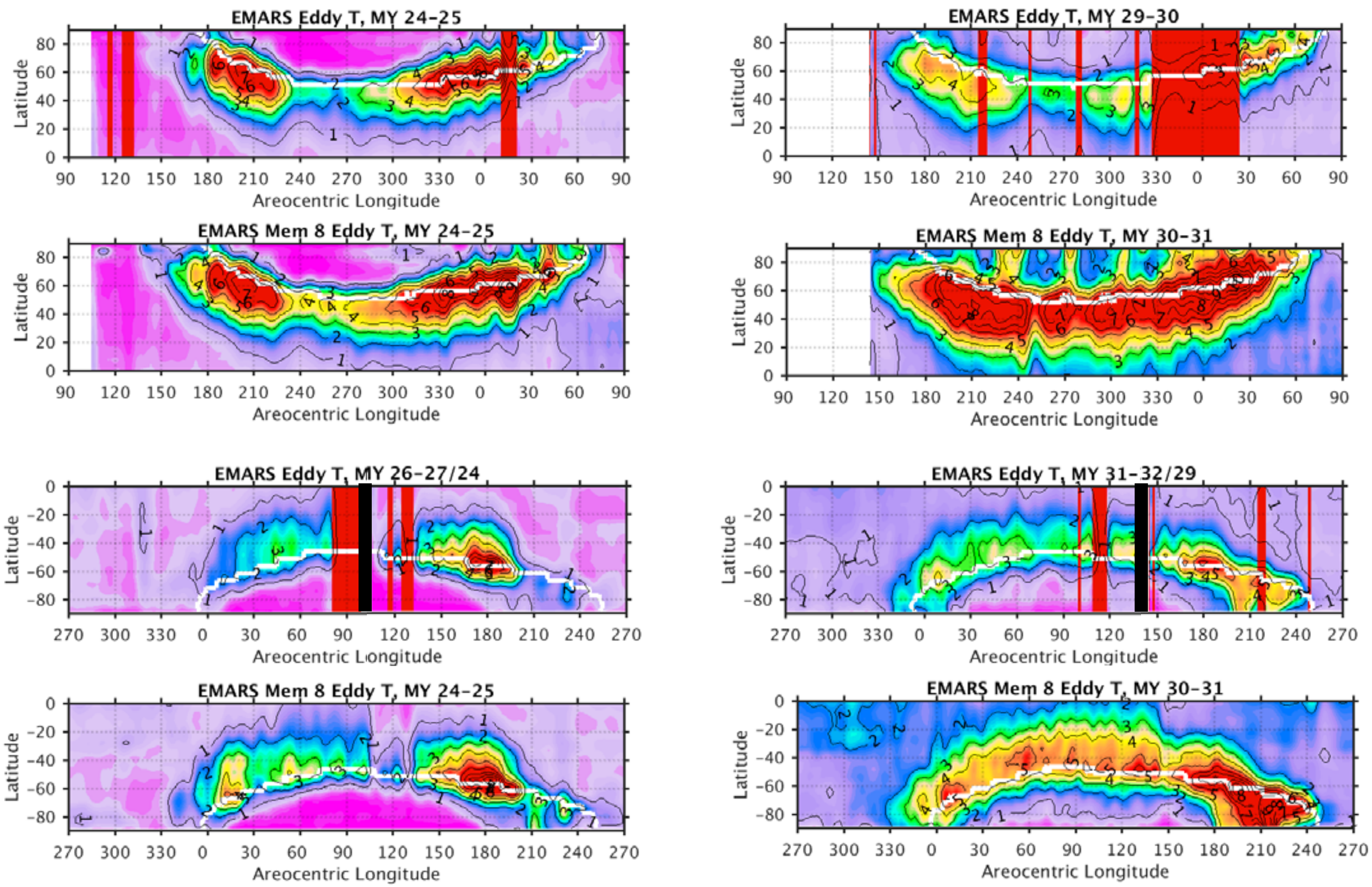
(d)

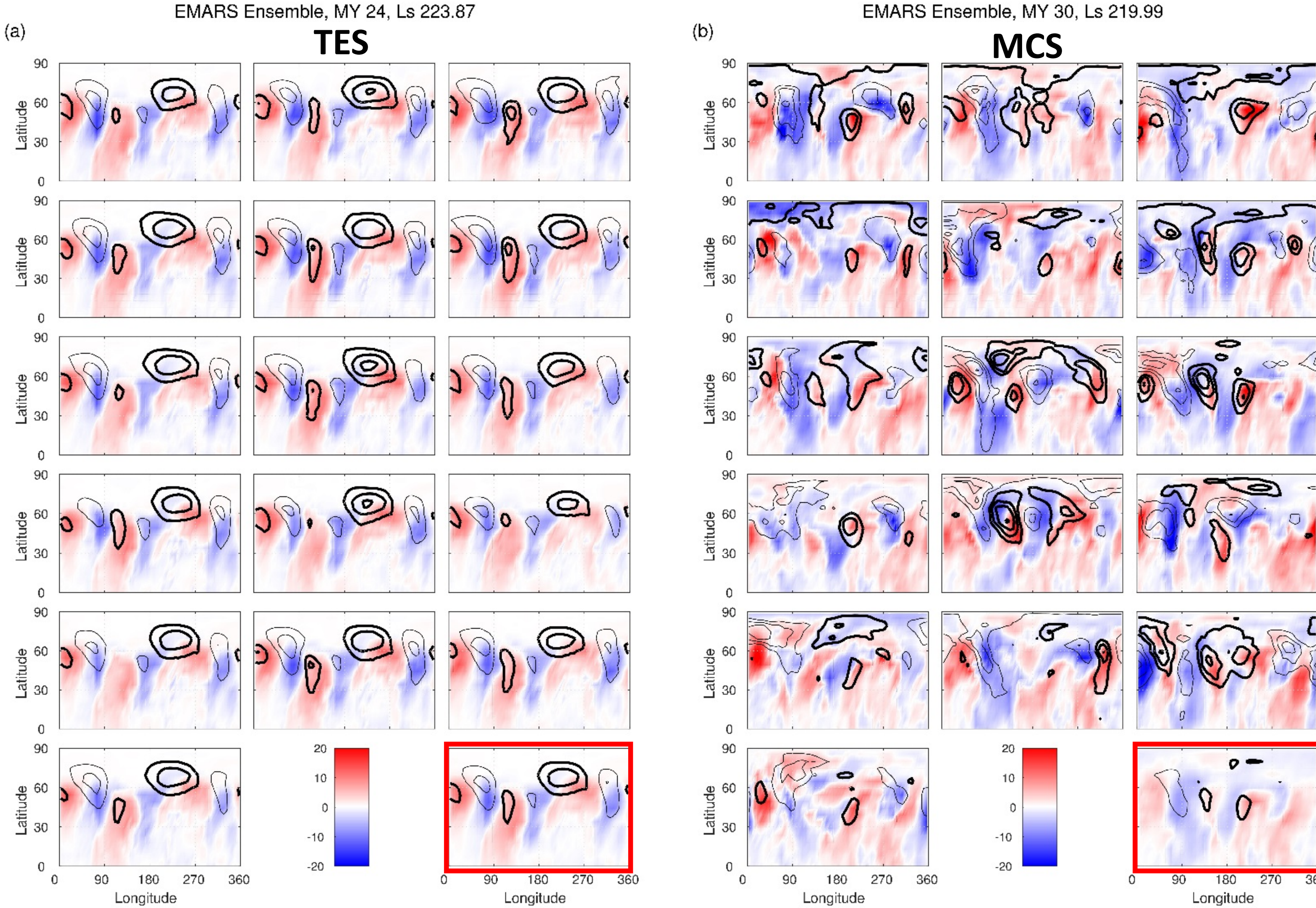


UK MGCM control run courtesy of MACDA team

Are Traveling Waves Robust?

Compare ensemble mean to representative ensemble member.
Similar amplitude / small ensemble spread implies greater convergence.





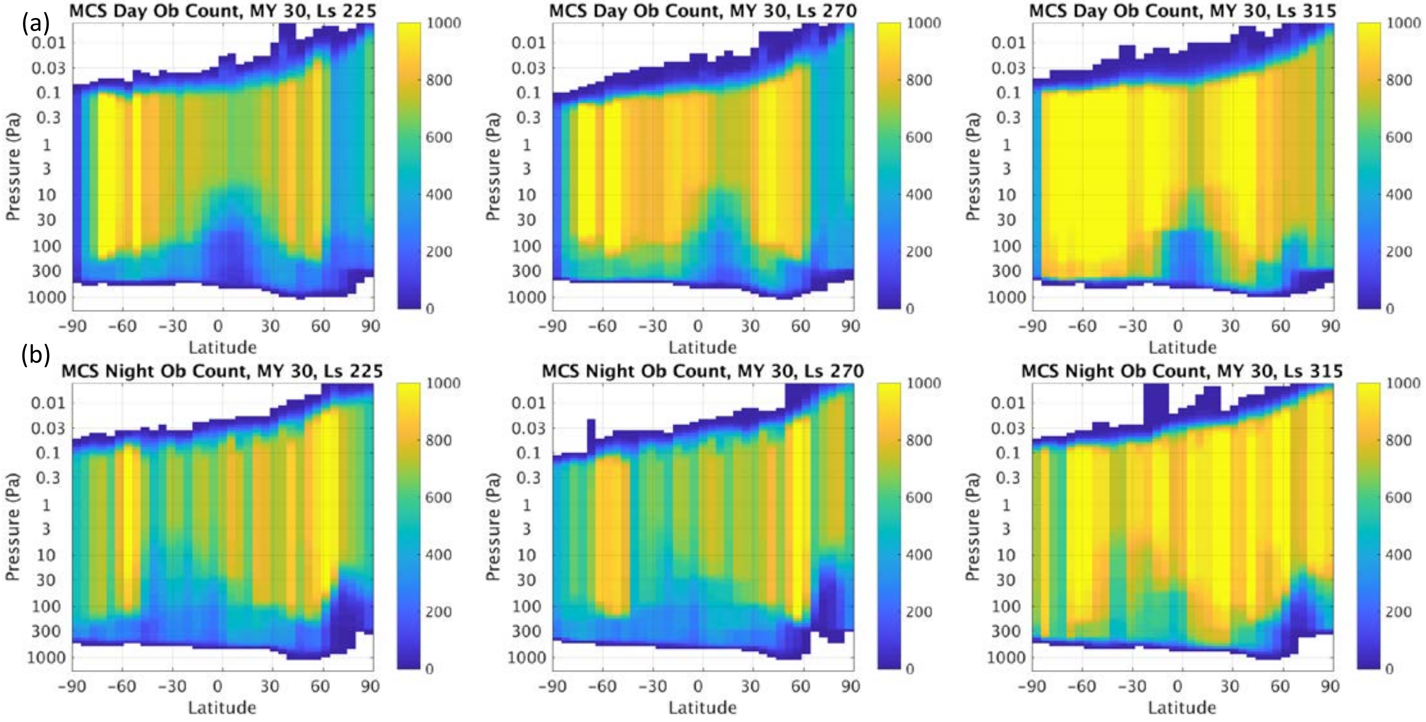
Ensemble Members vs **Mean**

Temperature (Shading) and Surface Pressure (Contours)

Sensitivity of Eddies to Observing System

MCS observation counts vs. Latitude

Note, less observations available in lowest few km, which is a challenge for data assimilation.



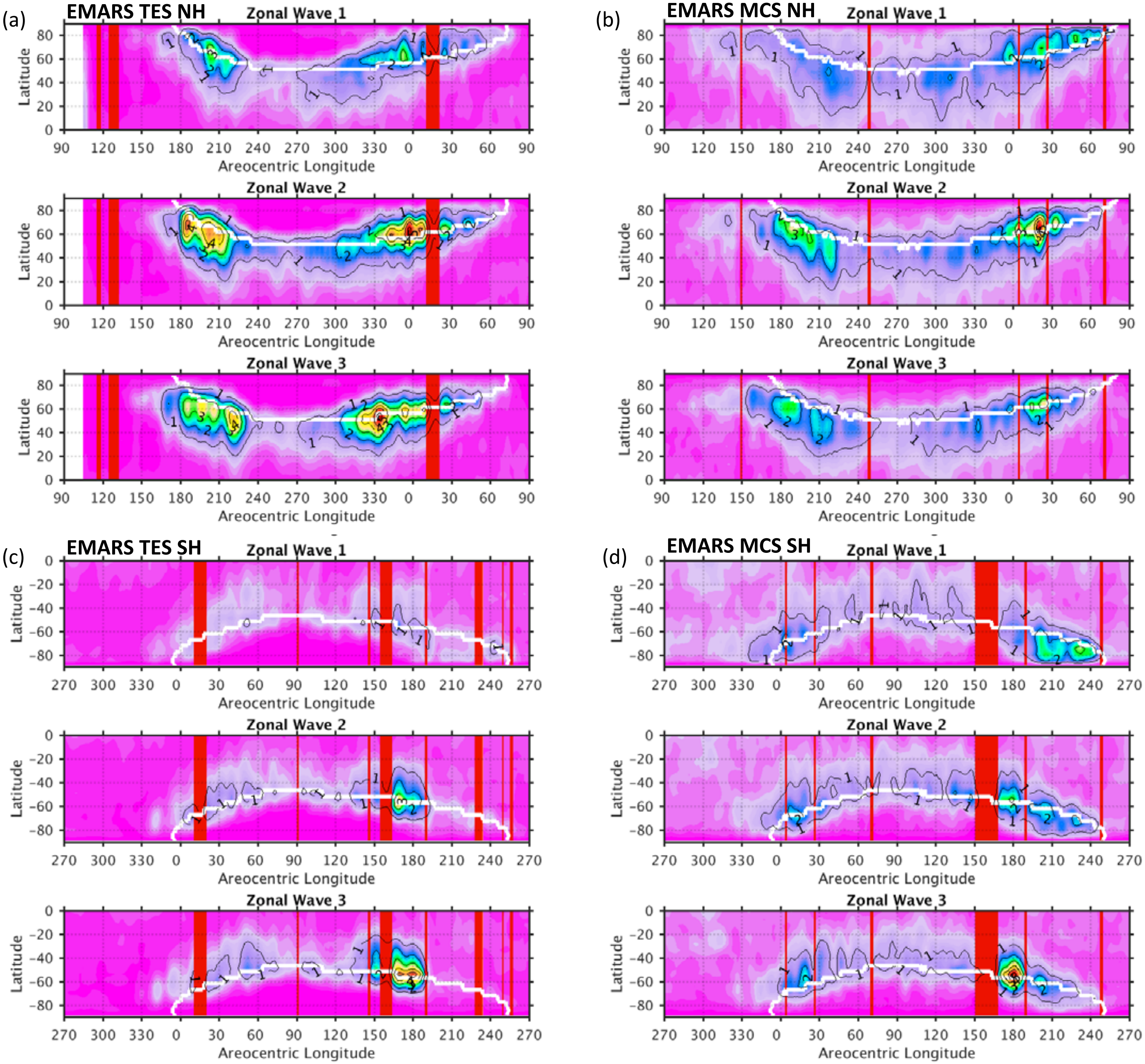
To what aspects of Mars atmosphere dynamics, observing system, and assimilation technique are wave systems sensitive?

Details of Eddies can be sensitive to:

Assimilation Run	Anomaly Correlation	Radiatively Active Water Ice Clouds	CO_2 Critical Temperature Filter	Level-Weighting Forward Operator	Observations Assimilated
EMARS MGCM control	-0.0346	Yes	N/A	N/A	None
MACDA V1.0	0.5766	No	Yes	Yes	TES
Alt EMARS: noTcrit	0.8471	Yes	No	Yes	TES
Alt EMARS: nolowerT	0.5720	Yes	Yes	Yes	TES only above 500 Pa
Alt EMARS: noclouds	0.8396	No	Yes	Yes	TES
Alt EMARS: wsingle	0.7812	Yes	Yes	No	TES
Alt EMARS: wsingle_noTcrit	0.8139	Yes	No	No	TES

- Model: including aerosol field and zonal mean state
- Forward Model: how to weight observations in vertical
- Observations: nadir vs. limb, vertical resolution, data quality
- Assimilation System Design

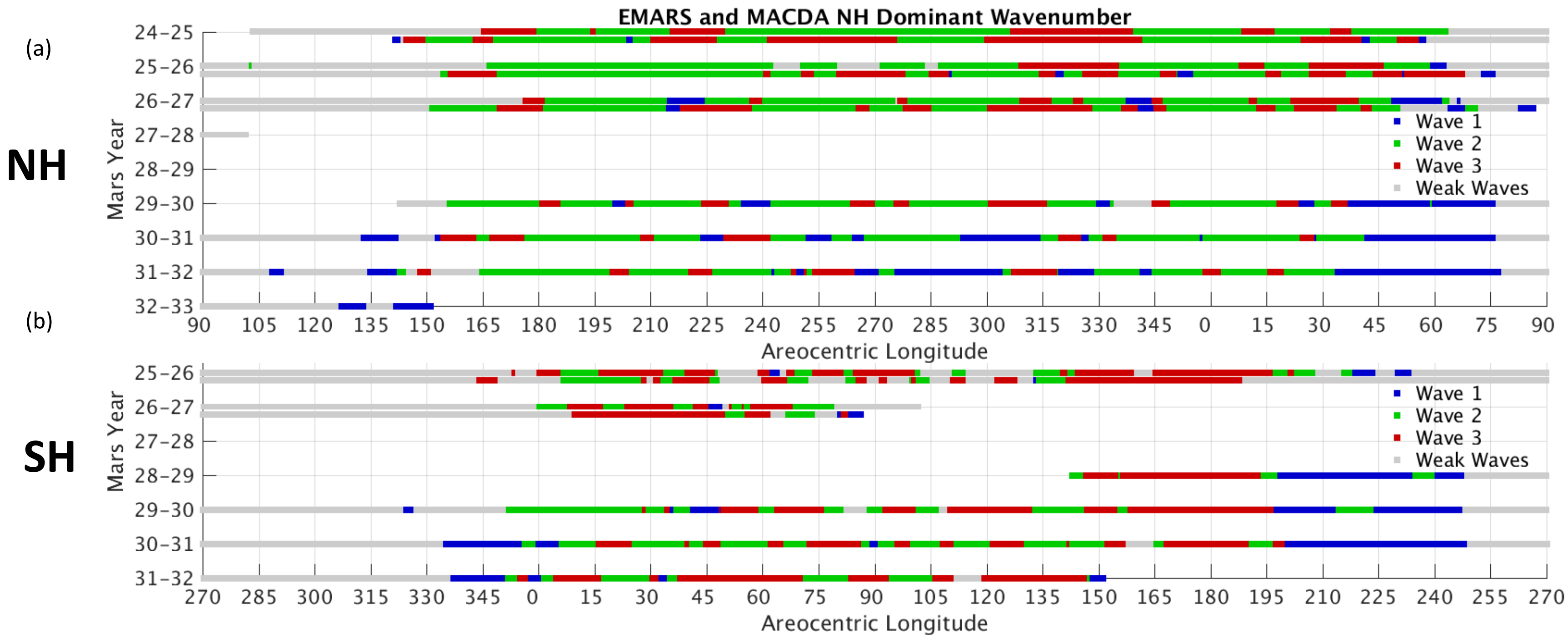
EMARS Eddies by Zonal Wavenumber



MY 24/25

MY 30/31

Wave Regime Diagram

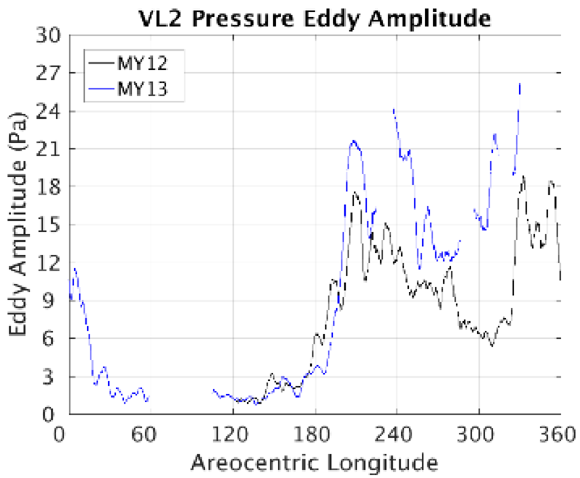


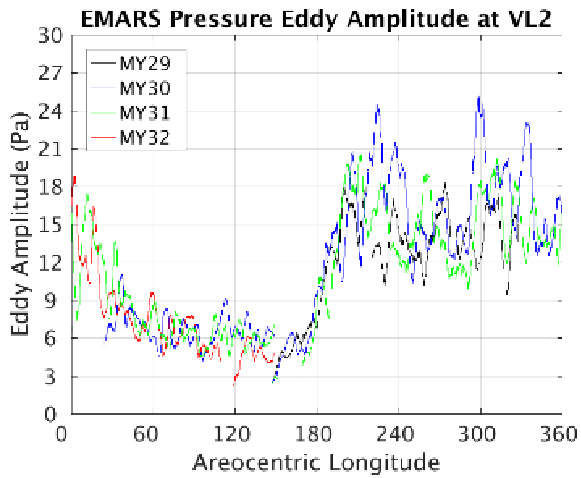
The maximum zonal mean eddy amplitude, for each hemisphere, time, and wavenumber is computed; the wavenumber with the greatest eddy amplitude is shown, unless <1 K.

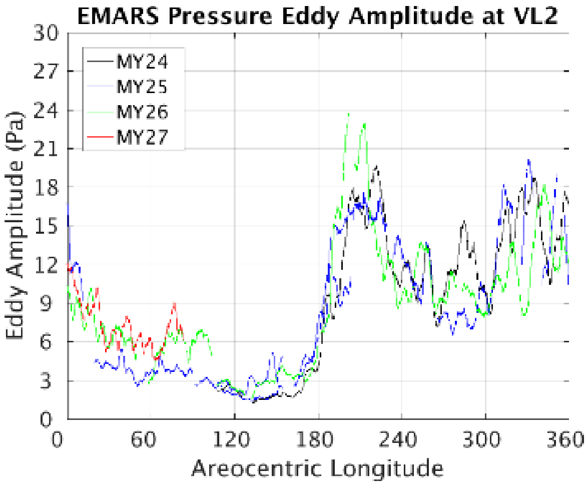
For TES, EMARS is plotted above MACDA

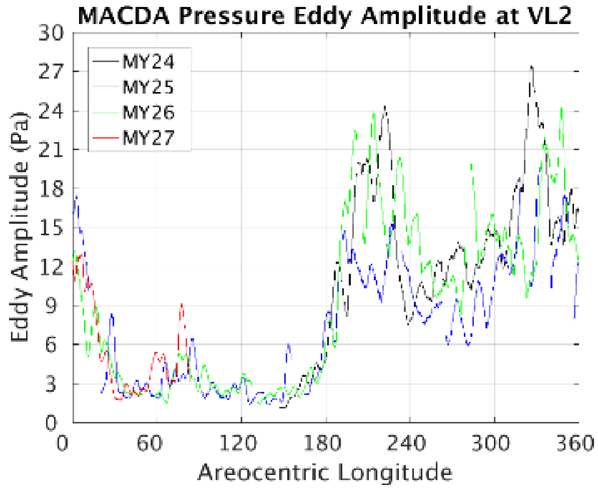
Do dominant wave regimes have a seasonality?

Surface Pressure: Reanalysis vs. Viking



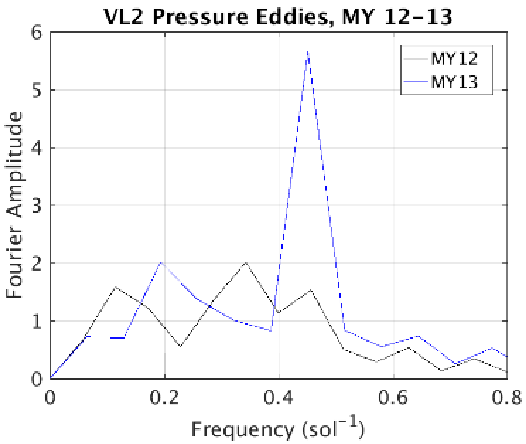


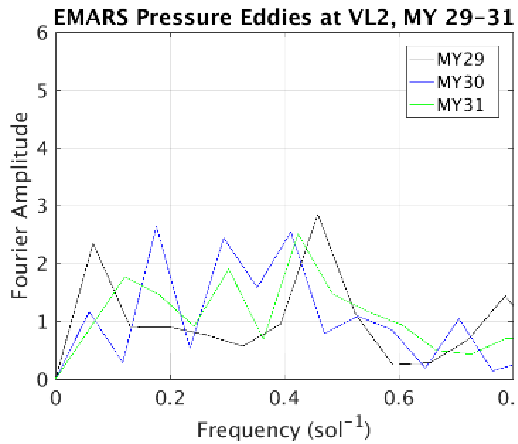


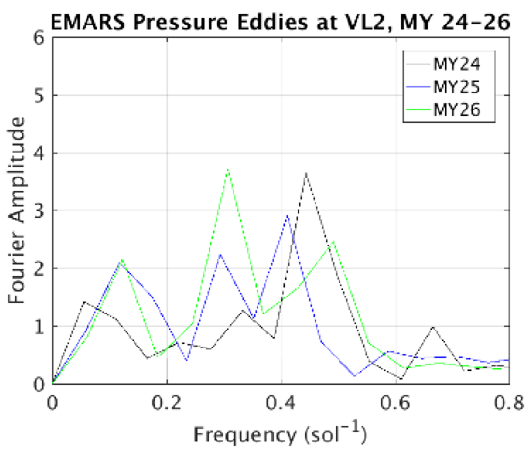


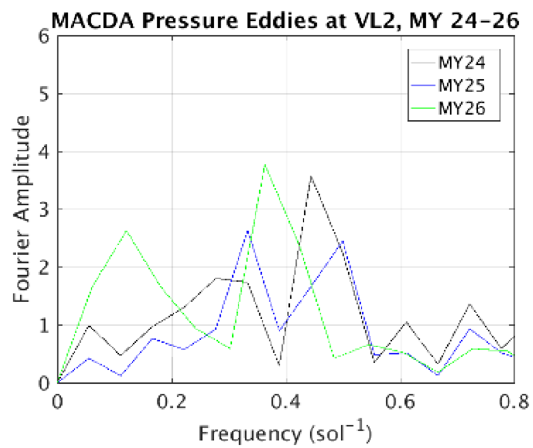
How do traveling waves compare to other observations?

Spectral Comparison of Waves









(h)

Each curve selected to display the 10 Ls when the surface pressure fourier amplitude in the 0.4 and 0.5 sol^-1 frequency (~2 sol period) is maximized.

Dataset	MY	VL 1 Ls	VL 2 Ls
Viking	12	335	325
Viking	13	No Data	236.7
Viking	14	321	No Data
EMARS	24	335	335
EMARS	25	315	315
EMARS	26	305	205
EMARS	29	305	235
EMARS	30	225	315
EMARS	31	315	305
MACDA	24	335	335
MACDA	25	335	335
MACDA	26	315	195

Wave 3 for Flushing Storms?

MY	Ls (Hinson et al., 2012)		Ls (EMARS)	
	Start	End	Start	End
24	219	230	215	230
	316	339	306	339
25	none	none	none	none
	316	330	308	336
26	228	242	236	240
	306	318	309	317

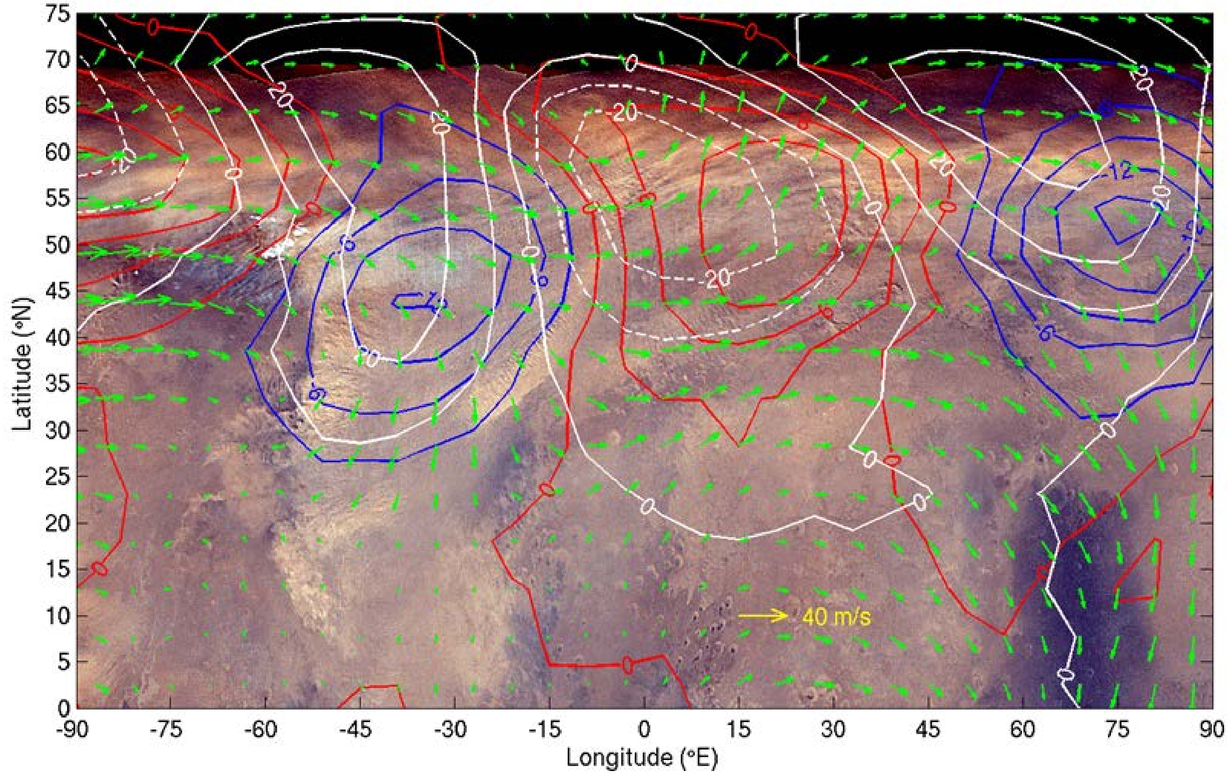
Comparison of the start and end Ls values of waves with wavenumber 3 in MY 24-26 in Hinson et al. (2012) [using radio science] and the corresponding wavenumber 3 periods in EMARS.

__Ongoing questions:__

What is the synoptic evolution of dust storms?

How predictable are traveling wave regimes?

EMARS synoptic map during flushing storm



Conclusions

- We have examined low level traveling waves in EMARS.
- Generally, convergence between EMARS and MACDA eddies (in wavenumber / phase / amplitude).
- Details of eddies can be sensitive to observing system, model configuration, and DA method.
- Vertical resolution of obs an important consideration.
- Spacecraft imagery and reanalyses together can provide insights on dust storm evolution.

Thank you!

- We plan to share the EMARS dataset with the community.
- Applications of reanalyses can include:
  - Comparing the reanalysis to new atmospheric **observations** for validation.
  - Using the reanalysis for **initial** and **boundary conditions** for global or regional models.
  - Testing new **model** physics and **parameterizations** in the assimilation system.
  - Understanding the atmospheric response to **aerosol** evolution.
  - Using reanalysis winds to understand **transport**.
  - Provide atmospheric states and their uncertainties for **engineering** studies.

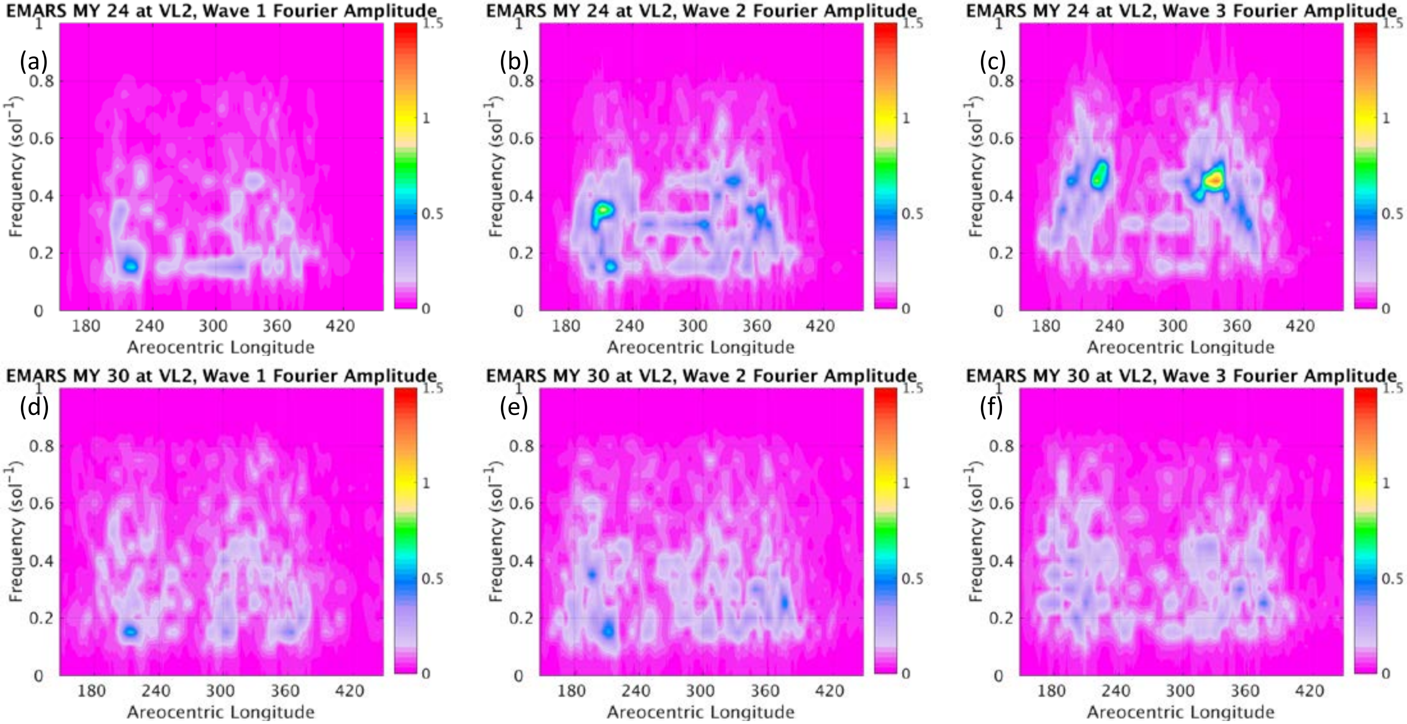
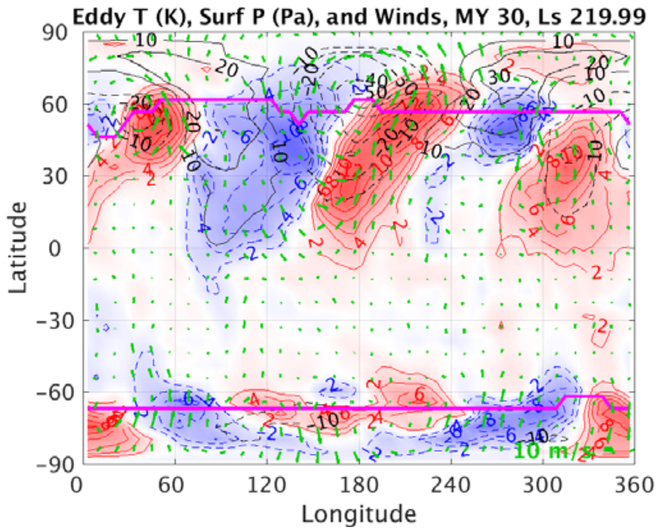


Figure 20: EMARS Fourier amplitudes of eddy temperature at the model level ~1 km above Viking Lander 2 during (a,b,c) MY 24 (TES era) and (d,e,f) MY 30 (MCS era) for zonal wavenumbers (a,d) 1, (b,e) 2, and (c,f) 3.



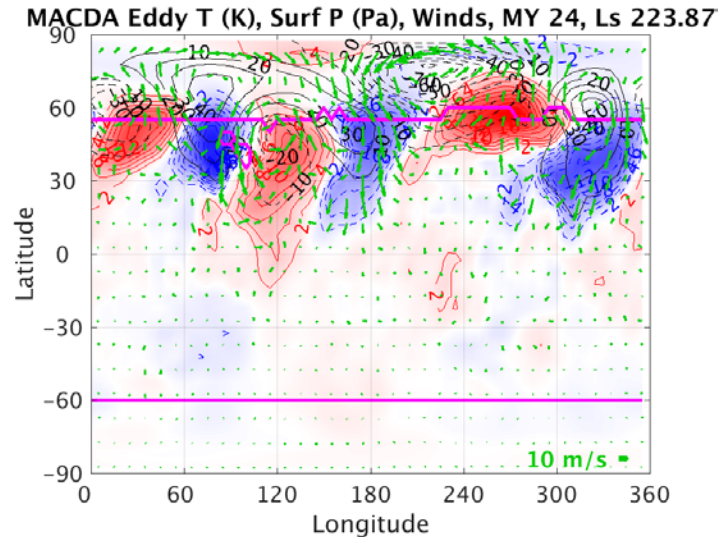


Figure 21: Synoptic map at the same time as Figure 1, except for MACDA plotted at model level 8 (sigma 0.9).

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, and (b) MY 30 Ls 220, which is during the MCS 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).