



# Equatorial Waves Associated with Dust Storms as Simulated in a Mars General Circulation Model

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## Abstract

Equatorial atmospheric waves provide a mechanism for variability on a wide range of timescales and for disturbances in one part of the tropics to influence other tropical locations around the globe. A Mars general circulation model is used to investigate how equatorial waves behave under different atmospheric dust loading scenarios and when perturbed by dust storms. Such waves may be important for understanding triggering of distant dust storms or additional dust lifting centers within large storms. Equatorial waves appear to change when dust storm sequences cross the equator or when background dust amounts significantly vary, with eastward- and westward-propagating waves within a wide spectral interval being amplified in general. Specifically, many low-frequency, long-wavelength equatorial waves become prominent during prescribed dust storm episodes. Their horizontal wave structures seen in the 100 Pa geopotential field show a resemblance to equatorial Rossby, Kelvin, and mixed Rossby–gravity waves. Waves with different wave periods and zonal wavenumbers evolve with time and interfere with each other, leading to complex time-dependent eddy patterns. This study shows that both dust storms and background dust can significantly influence the spectra and structures of eddies in the tropical Martian atmosphere.

*Unified Astronomy Thesaurus concepts:* [Solar system terrestrial planets \(797\)](#); [Mars \(1007\)](#); [Atmospheric dynamics \(2300\)](#); [Atmospheric circulation \(112\)](#)

## 1. Introduction

Observations show that major dust storms are associated with apparent changes in the Martian atmosphere (M. A. Kahre et al. 2017). The strong radiative effect of dust leads to warmer global mean temperature and accelerated overturning circulation (R. M. Haberle et al. 1993; R. J. Wilson & K. Hamilton 1996; M. A. Kahre et al. 2006; D. P. Mulholland et al. 2013; C. E. Newman & M. I. Richardson 2015; M. J. Wolff et al. 2017), and complex changes occur in eddies on timescales from  $\leq 1$  sol to several tens of sols (S. D. Guzewich et al. 2014; D. M. Kass et al. 2016; J. M. Battalio & H. Wang 2020; D. P. Hinson & R. J. Wilson 2024). While the influences of major dust storms on the zonal mean circulation and thermal tides have been established by previous work (J. R. Barnes et al. 2017), the impact on longer-timescale traveling waves remains understudied, with existing work mainly focused on the mid- to high latitudes (D. P. Hinson et al. 2012; S. J. Greybush et al. 2019; J. M. Battalio & H. Wang 2020; D. P. Hinson & R. J. Wilson 2021, 2024; D. P. Hinson 2025).

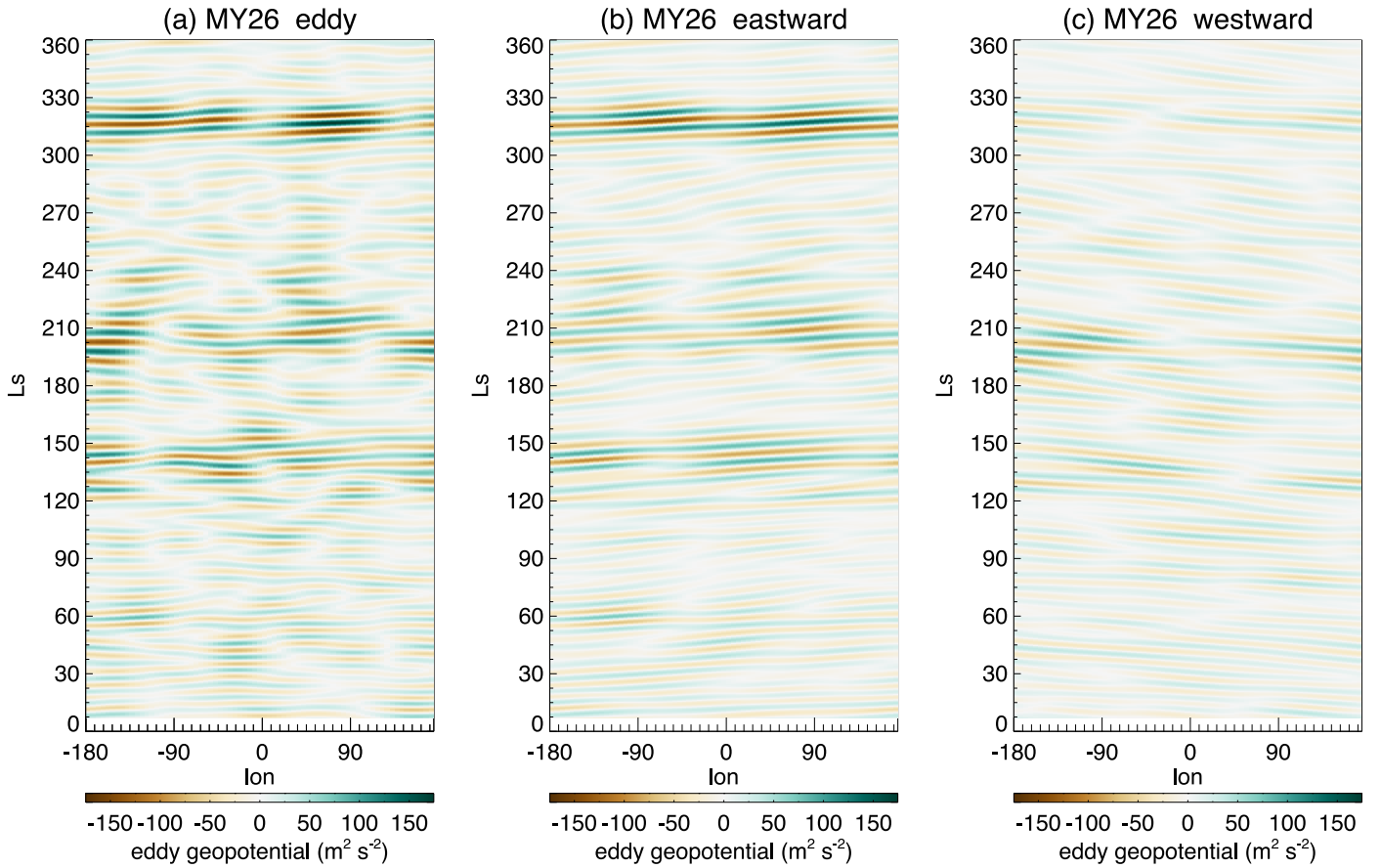
The Martian tropics (25°S–25°N, based on the obliquity of Mars) are known to host atmospheric waves with a wide range of frequencies, based on both orbital and surface-based Mars observations (D. Banfield et al. 2004, 2020; J. M. Battalio et al. 2022; D. P. Hinson & R. J. Wilson 2023; H. Wang et al. 2024). In the northern spring and summer when clouds are prevalent, H. Wang et al. (2024) have suggested that several different types of tropical long waves interact to generate the Tropical Cloud Oscillation (TCO). In the case of the TCO,

over timescales of 10–40 sols, the tropical cloud belt optical thickness is seen to oscillate with a dominant zonal wavenumber one pattern. While it is not clear whether the cloud optical thickness changes result from changes in water abundance, temperature, or vertical motion, tropical waves appear to have a significant dynamical impact on the Martian atmosphere. Such intraseasonal variability of tens of sols related to equatorial Kelvin and Rossby waves is reminiscent of terrestrial tropical variability in systems such as El Niño/Southern Oscillation (ENSO; e.g., H. A. Bridgman & J. E. Oliver 2014).

For the southern spring and summer, when dust storms are overall more active, how tropical waves respond to varied dust forcings and the impact of tropical waves on dust lifting are important questions. Orbiter imaging observations of the development of large dust storms on Mars often show distinct regional storms growing together into larger systems, crossing the equator at different times (e.g., M. J. Stausberg et al. 2005; B. A. Cantor 2007; H. Wang & M. I. Richardson 2015; J. M. Battalio & H. Wang 2021; H. Wang et al. 2023a). For example, in the case of the global dust storm in 2001, the main loci of dust lifting were nearly on opposite sides of the planet. As the initial storm center originating near northern Hellas became larger, a second center in Daedalia and Solis became active about 20 sols after the initial storm onset (M. J. Stausberg et al. 2005). The potential generation of distant responses to dust storm perturbations has raised the possibility of “teleconnections” in the Martian atmosphere (e.g., L. Montabone et al. 2008, O. Martinez-Alvarado et al. 2009, T. A. Mooring & R. J. Wilson 2015) akin to the wave transmission of information in the terrestrial tropical atmosphere, e.g., ENSO (D. B. Enfield 1989; H. A. Bridgman & J. E. Oliver 2014). It seems possible



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**Figure 1.** Eddy amplitudes as a function of longitude and  $L_s$  for geopotential ( $\text{m}^2 \text{s}^{-2}$ ) at the  $p = 100$  Pa pressure level for  $2.5^\circ\text{S}$  derived from the version 4 OpenMARS reanalysis for MY26. The eddies are composed of zonal wavenumber 1–4 waves with wave periods between 12 and 19 sols.

that tropical waves play a role in Martian dust storm growth through teleconnection.

Before investigations into tropical dust storm teleconnections can be undertaken, it is important to develop an understanding of whether/what tropical waves can be forced by dust storm perturbations and how they vary with dust loading. These questions are addressed in this paper.

### 1.1. Tropical Long Waves in Southern Spring and Summer from Reanalysis

The existence of different types of equatorial waves (e.g., Kelvin, equatorial Rossby, mixed Rossby–gravity (MRG), inertial gravity (IG) waves) was demonstrated by H. Wang et al. (2024) using the Mars Daily Global Maps (MDGMs; H. Wang & G. Gonzalez Abad 2022), UV ice optical depths (M. J. Wolff et al. 2019), and the Open-access to Mars Assimilated Remote Soundings (OpenMARS) reanalysis product (J. A. Holmes et al. 2020). However, their results focused on the tropical clouds in northern spring and summer. As discussed above, equatorial waves could also be relevant for the Martian dust cycle in southern spring and summer.

As a motivation for this paper, we show the amplitudes for zonal wavenumber  $k = 1$ –4 equatorial waves for the whole of Mars Year (MY) 26 using the version 4 OpenMARS dataset (Figure 1). MY26 has nominal dust storm activity and is among the Mars years when eddies were shown to be largely consistent across different reanalysis products (J. M. Battalio 2022). We therefore use MY26 for illustration here. Results from other Mars years vary and can sometimes be more

complex to decipher. The amplitudes shown are the geopotential eddy field on  $p = 100$  Pa at  $2.5^\circ\text{S}$ , with wave periods ( $P$ ) between 12 and 19 sols. The total amplitude and the corresponding eastward- and westward-propagating components are separately shown. The geopotential at each location and time step is calculated from the OpenMARS temperature–pressure profile and interpolated onto the 100 Pa pressure level. The waves were extracted using the method in Section 2.

Strong eddies are seen during  $L_s = 130^\circ$ – $150^\circ$ ,  $190^\circ$ – $210^\circ$ , and  $310^\circ$ – $330^\circ$  (Figure 1). While the first  $L_s$  period roughly corresponds to the TCO (H. Wang & G. Gonzalez Abad, 2022; H. Wang et al. 2024), the other two correspond to major dust storms (L. Montabone et al. 2015; H. Wang & M. I. Richardson 2015; D. M. Kass et al. 2016; J. M. Battalio & H. Wang 2021). Thus, there could be a connection between tropical waves and dust storms.

In this paper, we use simplified numerical experiments to examine how cross-equatorial dust storms might perturb the tropical atmosphere and excite or modify tropical waves. Specifically, we use a Mars general circulation model (GCM) with prescribed dust distributions inspired by observations to examine the behaviors of equatorial waves under various dust scenarios.

In Section 2, we describe the methodology, including a brief description of the GCM and numerical experiment design. Section 3 characterizes the modeled equatorial waves and examines their sensitivity to various dust scenarios. Section 4 provides a summary. Supplementary Figures (Figures A1–A8) can be found in the Appendix.

**Table 1**  
Dust Scenarios Used in Simulations

| Scenario         | Setup                           | Storm Period                        |
|------------------|---------------------------------|-------------------------------------|
| Reference        | no_storm                        | none                                |
| Case1_MY32A      | no_storm + MY 32A               | $L_s = 205^\circ\text{--}225^\circ$ |
| Case2_MY33C      | no_storm + MY 33C               | $L_s = 320^\circ\text{--}336^\circ$ |
| Exp1_Acidalia32A | no_storm + Acidalia_sequence    | $L_s = 205^\circ\text{--}225^\circ$ |
| Exp2_Acidalia32C | no_storm + Acidalia_sequence    | $L_s = 305^\circ\text{--}325^\circ$ |
| Climatology32    | MY32 (L. Montabone et al. 2015) | MY32 observed                       |
| Climatology33    | MY33 (L. Montabone et al. 2015) | MY33 observed                       |
| Scaled32         | Reference scaled to MY 32       | MY32 observed                       |

**Note.** NetCDF files can be found in supporting material.

## 2. Methodology

This section describes the model setup (Section 2.1), simulation design (Section 2.2), and analysis technique (Section 2.3).

### 2.1. Model

The MarsWRF GCM (M. I. Richardson et al. 2007; A. D. Toigo et al. 2012) is employed in this study. The model is equipped with different options for physics parameterizations and has been widely used in studies of the Martian  $\text{CO}_2$ , water, and dust cycles and atmospheric circulation (e.g., C. E. Newman et al. 2019; A. D. Toigo & D. W. Waugh 2022).

The model setup is the same as that in H. Wang et al. (2023b) except that the dust optical properties of M. J. Wolff et al. (2009) instead of those of R. T. Clancy & S. W. Lee (1991) are used in the correlated- $k$  distribution radiative transfer scheme (M. A. Mischna et al. 2012). The M. J. Wolff et al. (2009) dust properties result in a slightly lower atmospheric heating rate. As a result, for the reference run in Section 2.2, the simulated temperature at  $z \sim 25$  km altitude at low to mid-latitudes is about 1–3 K colder than that from the corresponding simulation in H. Wang et al. (2023b). For context, the Mars Reconnaissance Orbiter (MRO) Mars Climate Sounder (MCS) temperature retrievals have a precision of 0.5–2 K, and the differences between the Mars Global Surveyor Thermal Emission Spectrometer and Radio Science temperature observations are typically 1–2 K between  $z = 20$  and 30 km (D. P. Hinson et al. 2004; A. Kleinböhl et al. 2009, 2017). However, at high latitudes, the simulated zonal mean temperature using the two dust optical properties can result in differences of  $\sim 8$  K at  $z \sim 25$  km near perihelion. This paper focuses on the equatorial region far from the high latitudes.

The model is run on a staggered Arakawa C-grid at  $2^\circ$  longitude  $\times$   $2^\circ$  latitude horizontal spacing  $\times$  53  $\eta$  terrain-following vertical levels. Model output is saved every 2 Mars hours. Each run starts from a restart file of a previously spun-up reference run (Section 2.2) and is driven by its own yearly repeatable dust scenario. Each run lasts several (up to 10) Mars years. Analysis in this paper is performed after the first simulation year of each run. Unless specified otherwise, the results presented are from the second simulation year, which is representative of the general wave behavior (Section 3).

### 2.2. Simulations

The simulations performed for this study are driven by several prescribed spatially and temporally varying dust

scenarios (Table 1). The reference simulation uses the “no-storm” dust scenario derived and described in H. Wang et al. (2023b). This scenario is based on the minimum amount of background dust in the L. Montabone et al. (2015) climatology for MY24–MY34. Other simulations superpose additional dust storms over the no-storm dust scenario (Figure 2).

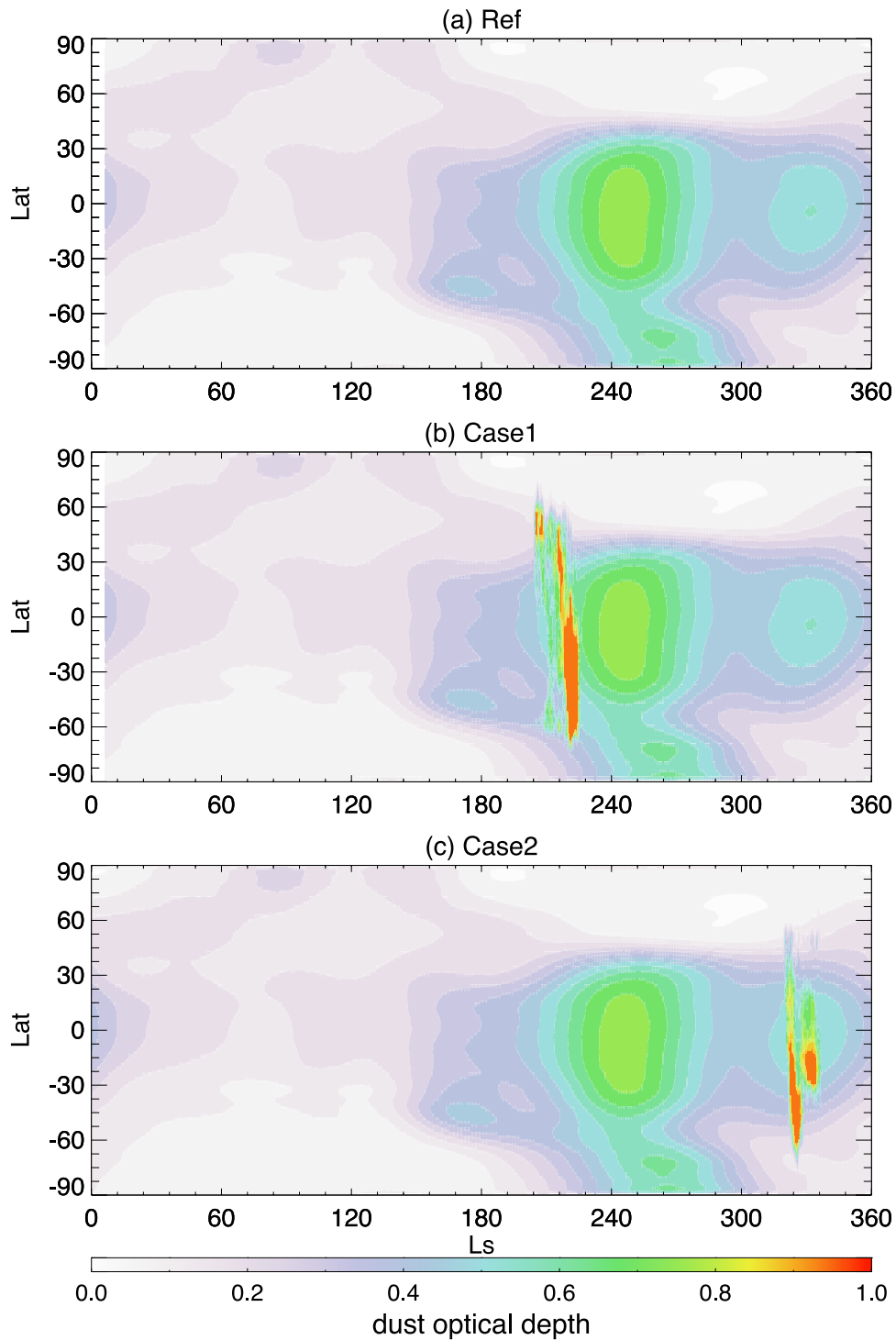
The additional dust storms in Case1\_MY32A are from the Mars Dust Storm Sequence Dataset (MDSSD) for  $L_s = 205^\circ\text{--}225^\circ$  of MY32 (M. Saidel et al. 2022), which result in the MY32 “A” storm (D. M. Kass et al. 2016). During this period, a dust storm episode composed of several dust storm sequences from different regions occurred (H. Wang et al. 2023a). The spatial coverage of the episode is shown in Figure 3(a) using the storm occurrence frequency of each pixel. Dust storm sequences through the Acidalia–Chryse, Utopia–Isidis, Arcadia–Amazonis, and Hellas–Valles Marineris corridors are all involved, and their time series for storm area are shown in Figure 3(c). Dust storm sequences that occur before  $L_s \sim 219^\circ$  merge into a large dust storm sequence afterward. Figure 2(b) shows the latitude– $L_s$  distribution of dust storm members of the corresponding dust storm sequences. The dust storm episode progressed from the northern hemisphere in the first half of the development history to the southern hemisphere in the second half. Several relatively large dust storm members occurred near the equator during  $L_s \sim 215^\circ\text{--}218^\circ$ .

The added dust storms in Case2\_MY33C are from the dust storm episode during  $L_s = 320^\circ\text{--}336^\circ$  of MY33 in the MDSSD. Two dust storm sequences are observed sequentially through the Acidalia–Chryse channel (Figure A2), resulting in the MY33 “C” storm. Relatively large dust storm members occurred near  $L_s \sim 321^\circ$  and  $328^\circ$  (Figure A1).

For each dust storm member in Figure 3(b), we assign a  $9.3 \mu\text{m}$  absorption column dust optical depth (scaled to  $p = 610$  Pa) for thin ( $\tau = 0.5$ ), medium ( $\tau = 1$ ), or thick ( $\tau = 2$ ) storms (MDGMs). The assigned values are within the range spanned by the L. Montabone et al. (2015) climatology and are meant to represent dust storm instances (locations and strengths) based on subjective user inspections of Mars Daily Global Maps (H. Wang et al. 2023a). These patches of optical depth increase (see examples in Figure A2) are added to the “no-storm” reference dust scenario during the  $L_s$  period of the dust storm episode. The resulting dust scenario is used to drive the simulation.

Time series of the global mean dust optical depth for each dust scenario are shown in Figure A3. By design, the curves for these cases follow the no-storm reference scenario outside dust storm episodes. A large peak occurs during  $L_s = 205^\circ\text{--}225^\circ$  for Case1\_MY32A and during  $L_s = 320^\circ\text{--}336^\circ$  for Case2\_MY33C.

The rest of the simulations in Table 1 are sensitivity runs. Exp1\_Acidalia32A and Exp2\_Acidalia32C were designed to test the effect of a single dust storm sequence if it occurred in different seasons. The dust storms are prescribed using the Acidalia sequence (red line in Figure 3(c)) and the merged sequence (purple line in Figure 3(c)) for Case1\_MY32A. Thus, the dust storm members in the Utopia and Arcadia channels are excluded, and the merged sequence is considered as an extension of the Acidalia sequence. For simplicity, we refer to the combination as the “Acidalia sequence.” Exp1\_Acidalia32A adds the dust storm members during  $L_s = 205^\circ\text{--}225^\circ$ ; Exp2\_Acidalia32C, during  $L_s = 305^\circ\text{--}325^\circ$ .



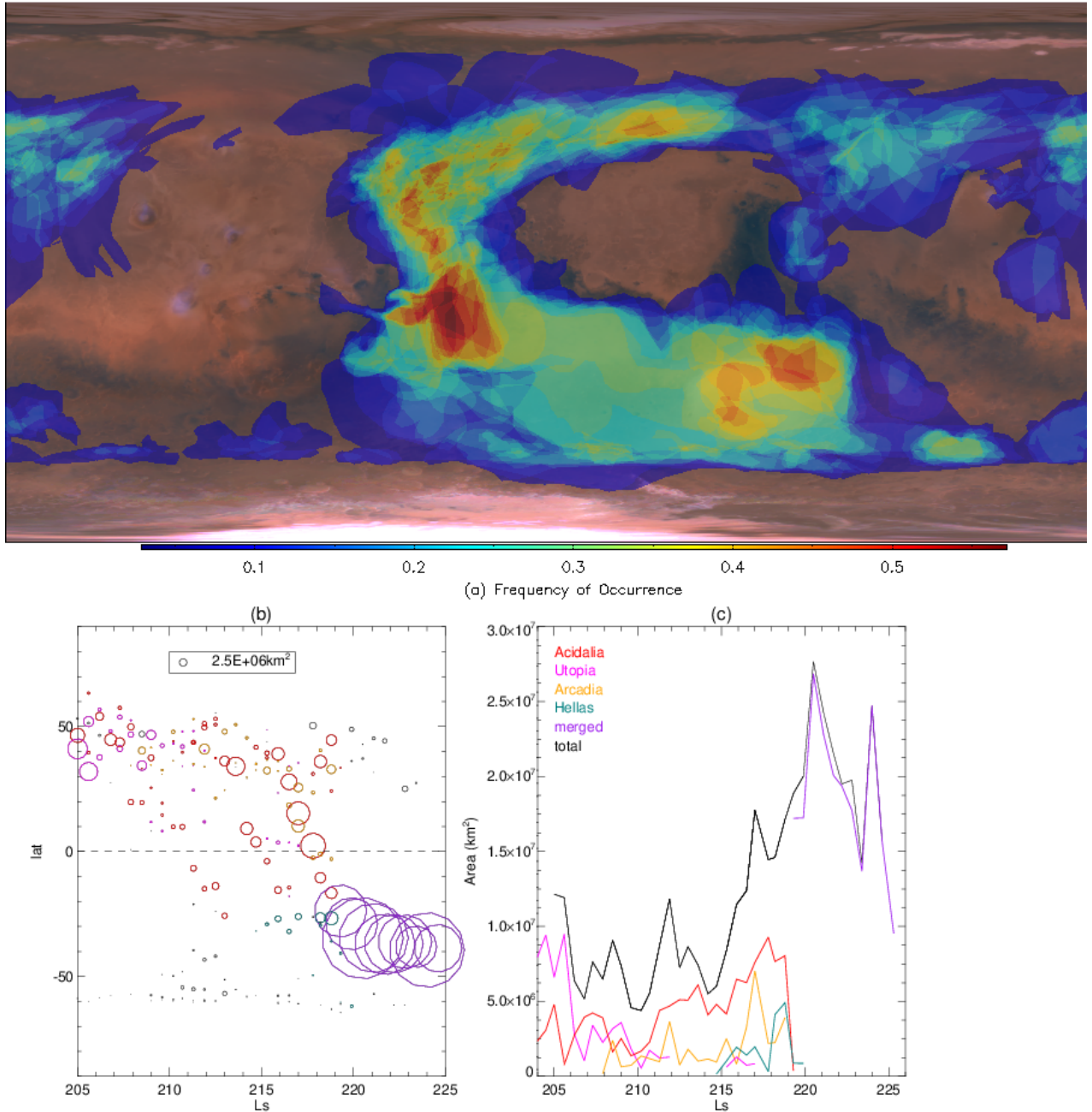
**Figure 2.** Zonal mean  $9.3\ \mu\text{m}$  absorption dust optical depth (scaled to 610 Pa) as a function of latitude and  $L_s$ , used in (a) reference, (b) Case1\_MY32A, and (c) Case2\_MY33C.

To investigate equatorial waves under commonly used dust conditions, we conducted runs using the L. Montabone et al. (2015) dust climatology for MY32 (Climatology32) and MY33 (Climatology33; Figure A3). Although the climatology agrees with the MDSSD on large regional and global scales (L. Montabone et al. 2015; H. Wang et al. 2023a), the two datasets can differ significantly on the locations, shapes, and timings of individual dust storm instances (Figure A2). During the MRO era, the dust climatology heavily relies on the MCS dust profile retrievals,

which often have difficulty reaching the surface. Furthermore, the horizontal coverage of MCS is much sparser in comparison with that of Mars Daily Global Maps. As a consequence, the gridded dust climatology inevitably has many low reliability values and may not be accurate in capturing the fine details (L. Montabone et al. 2015). However, the climatology provides quantitative dust optical depths and is highly convenient to use.

To further test the effect of spatial dust distribution, we synthesize a dust scenario (Scaled32) by scaling the reference





**Figure 3.** Dust storm episode observed during MY32  $L_s = 205^\circ$ – $225^\circ$ . (a) Latitude–longitude distribution of storm occurrence frequency during the episode. (b) Latitude– $L_s$  distribution of the centroids of dust storm members. Symbol size is proportional to storm area. Symbol color follows the legend in panel (c). (c) Area ( $\text{km}^2$ ) of dust storm sequences as a function of  $L_s$  during the episode. Color keys indicate the origination regions of dust storm sequences. The purple line corresponds to the merged dust storm sequence after  $L_s = 219^\circ$ . The black line corresponds to the sum of all dust storm sequences.

no-storm dust scenario on each sol so that the global mean dust optical depth time series matches that of Climatology32. Thus, even though Climatology32 and Scaled32 have the same global mean dust each sol, their spatial dust distribution differs, because the former has embedded dust storms, while the latter does not.

### 2.3. Wave Analysis

This study focuses on nontidal traveling waves near the equator during  $L_s = 180^\circ$ – $360^\circ$ . For each atmospheric variable

of interest, we follow the method in H. Wang et al. (2023b) to first remove the seasonal cycle at each grid point by subtracting the 60-sol running mean. Then, we perform a Morlet wavelet transform (C. Torrence & G. P. Compo 1998; Y. Liu et al. 2007) to project the signal onto a set of wavelet scales (corresponding to different wave oscillation periods) at each time step. We filter out the eddies with wave periods  $P < 1.7$  sols. An inverse wavelet transform is performed for the relevant wavelet scales to obtain the corresponding 1D time series. By design, the wave periods of the filtered eddies are within  $P = 1.7$ –60 sols.

The variable of interest is primarily the geopotential at  $p = 100$  Pa. This pressure level is about  $z = 20$  km above the 610 Pa reference pressure level. Due to the large topography range on Mars, surface pressure can vary by 600 Pa or more near the equator. For example, in the no\_storm simulation, surface pressure at  $1^\circ\text{S}$  varies between about 200 Pa and 860 Pa during  $L_s = 180^\circ\text{--}360^\circ$ . To simplify analysis in this initial study,  $p = 100$  Pa is used to minimize the need for extrapolating atmospheric variables below the surface for high topography regions (e.g., Tharsis) while keeping within roughly a couple of atmospheric scale heights for low topography regions. The zonal mean zonal winds near  $z = 20$  km are several meters per second for the  $L_s$  periods studied. (Figure A4). However, there are strong wind shears along both latitude and height directions, which will likely distort wave properties. Selected results for other variables and vertical levels are included in supplementary figures and discussed briefly in Section 3.2.2.

The time series from the wavelet analysis are combined along each latitude into longitude versus time 2D arrays for subsequent analysis. The 2D arrays are decomposed into eastward- and westward-propagating components (e.g., Figure 1) through forward and inverse 2D fast Fourier transforms (FFTs). This is achieved by summation of the waves reconstructed from the 2D Fourier spectral domain for the corresponding propagation directions.

The spacetime spectrum for each latitude and time step is obtained from the 2D longitude–time array derived from the wavelet and FFT analysis using the following procedure. For each wavelet scale (i.e., wave period equivalent) and propagation direction, we perform a 1D zonal Fourier transform at each time step to derive the amplitudes and phases of different zonal wavenumbers. At each time step, the wave amplitudes are organized according to wave period (corresponding to wavelet scale) and zonal wavenumber into a spectrum for each propagation direction (M. Wheeler & G. N. Kiladis 1999). The eastward and westward spectra can be combined into a single spectrum at each time step for visualization.

### 3. Results

This section first characterizes the distributions, spectra, and structures of the waves from the reference, Case1\_MY32A, and Case2\_MY33C runs (Sections 3.1–3.4) and then investigates the sensitivity of the waves to other dust scenarios (Section 3.5).

#### 3.1. $L_s$ –Longitude Distribution

Figure 4 shows the  $L_s$ –longitude plot (i.e., Hovmöller diagram) of eastward- and westward-propagating eddies with  $P = 7\text{--}30$  sols in the geopotential field at  $p = 100$  Pa and  $1^\circ\text{S}$  for the reference, Case1\_MY32A, and Case2\_MY33C simulations. For easier comparison, solid lines bracket the  $L_s$  periods of prescribed dust storm episodes, and dashed lines indicate first occurrence of significant dust storm members near the equator. For all simulations, Figure 4 indicates that both eastward- and westward-propagating waves are composed of a variety of zonal wavenumbers and wave periods. Higher zonal wavenumbers (shorter wavelengths) correspond to more oscillations along the longitude dimension, and higher frequencies correspond to more cycles along the time dimension.

Apparent changes in wave characteristics (e.g., wavelength, frequency, amplitude) can be seen during the  $L_s$  periods with

prescribed dust storms, suggesting that dust storm episodes can significantly excite/modify waves in the Martian tropics. For Case2\_MY33C, both the eastward and westward waves are enhanced soon after the initiation of the MY33C dust storm episode (Figures 4(c) and (f)). This episode developed toward the equator rapidly (Figure A1), and the wave intensification occurred soon after the initiation of the episode. For Case1\_MY32A, significant intensification (especially eastward waves) is seen about  $10^\circ$  of  $L_s$  after the start of the dust storm episode (Figure 3). The timing appears to correspond to the occurrence of near-equatorial dust storm members (around dashed lines in Figures 4(b) and (e)).

### 3.2. Spacetime Spectrum

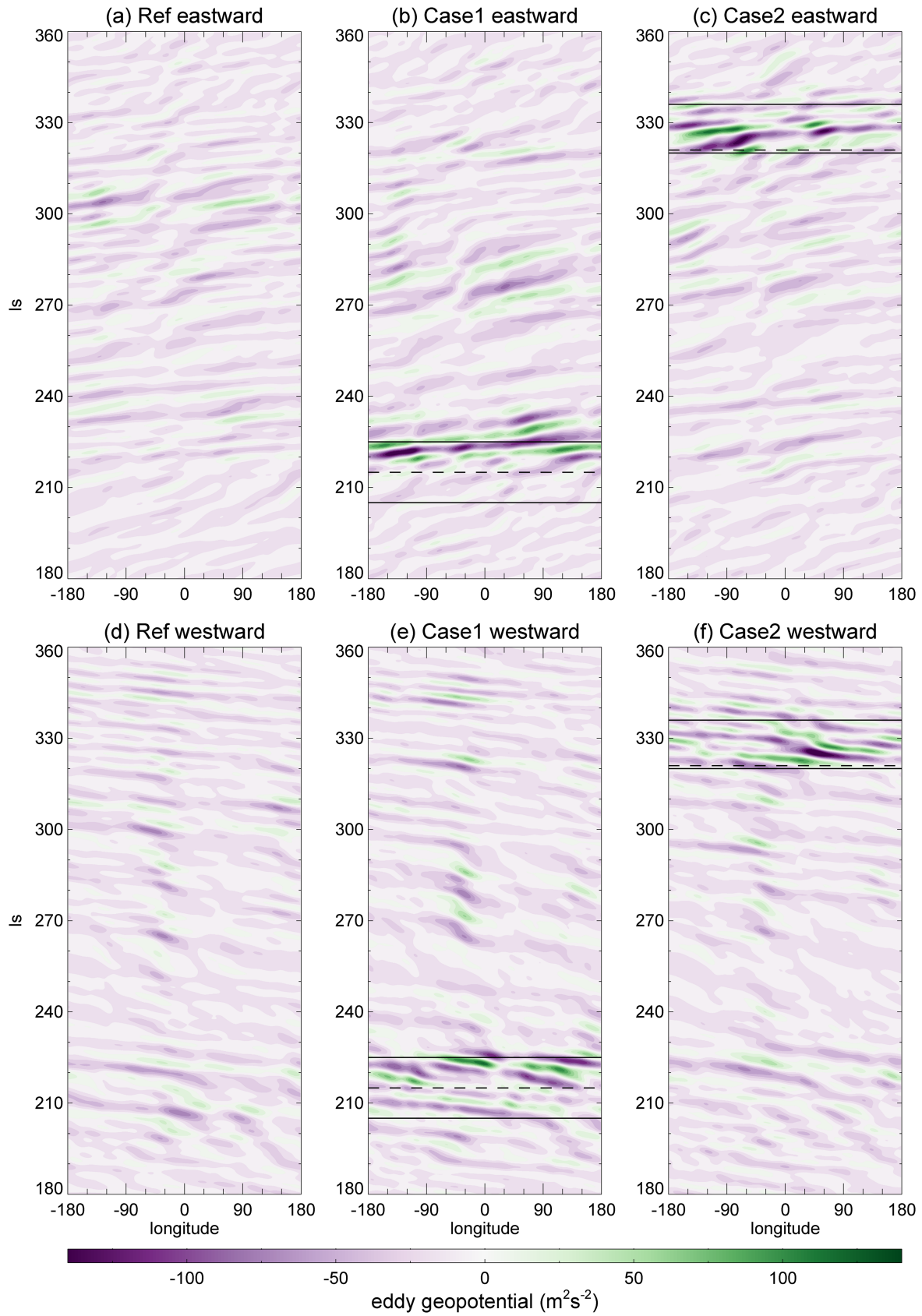
#### 3.2.1. Geopotential at 100 Pa

In Figure 5, we examine the wave frequency ( $f = 1/P$ ) versus zonal wavenumber ( $k$ ) spectrum for equatorial waves during the prescribed dust storm episodes. Wave amplitudes for the  $p = 100$  Pa geopotential between  $15^\circ\text{S}$  and  $15^\circ\text{N}$  are averaged during  $L_s = 215^\circ\text{--}225^\circ$  for Case1\_MY32A and  $L_s = 325^\circ\text{--}335^\circ$  for Case2\_MY33C. These  $L_s$  periods are examined owing to the apparent changes in wave characteristics (Figure 4). Westward- and eastward-propagating waves are plotted as negative and positive zonal wavenumbers, respectively. The corresponding spectra for the reference run are shown in Figures 5(a) and (e) for comparison.

For the reference run, zonal wavenumber  $k = \pm 1$  and  $k = \pm 2$  waves are prominent over a broad wave frequency range. Eastward waves are mostly within  $f \sim 0.12\text{--}0.56$  cycles/sol ( $P \sim 1.7\text{--}8$  sols), with phase speed of  $c \sim \pm 29$  to  $\pm 134$   $\text{m s}^{-1}$  for  $k = \pm 1$  and  $c \sim \pm 15$  to  $\pm 67$   $\text{m s}^{-1}$  for  $k = \pm 2$ ; westward waves are mostly within  $f \sim 0.05\text{--}0.56$  cycles/sol ( $P \sim 1.7\text{--}20$  sols), with  $c \sim \pm 12$  to  $\pm 134$   $\text{m s}^{-1}$  for  $k = \pm 1$  and  $c \sim \pm 6$  to  $\pm 67$   $\text{m s}^{-1}$  for  $k = \pm 2$ . Many of these wave frequencies were reported in previous observations (D. Banfield et al. 2004, 2020; J. M. Battalio, 2022; D. P. Hinson & R. J. Wilson 2023). Some zonal wavenumber  $k = \pm 4$  waves with  $f \sim 0.16\text{--}0.17$  cycles/sol ( $P \sim 6\text{--}7$  sols,  $c \sim \pm 8.5$   $\text{m s}^{-1}$  to  $\pm 10$   $\text{m s}^{-1}$ ) are also discernible in the reference run. The composition of the wave spectrum also changes with the season. The strongest wave for  $L_s = 215^\circ\text{--}225^\circ$  propagates eastward with  $k = 1$ ,  $f \sim 0.17$  cycles/sol ( $c \sim 41$   $\text{m s}^{-1}$ ), and that for  $L_s = 325^\circ\text{--}335^\circ$  propagates westward with  $k = -1$ ,  $f \sim 0.16$  cycles/sol ( $c \sim -38$   $\text{m s}^{-1}$ ). Generally speaking, equatorial waves with shorter wave periods ( $P < \text{several sols}$ ) are more likely IG, fast Kelvin, or fast MRG waves, and those with longer wave periods are more likely Rossby, slow Kelvin, or slow MRG waves (T. Matsuno 1966; D. P. Hinson & R. J. Wilson 2023; H. Wang et al. 2024).

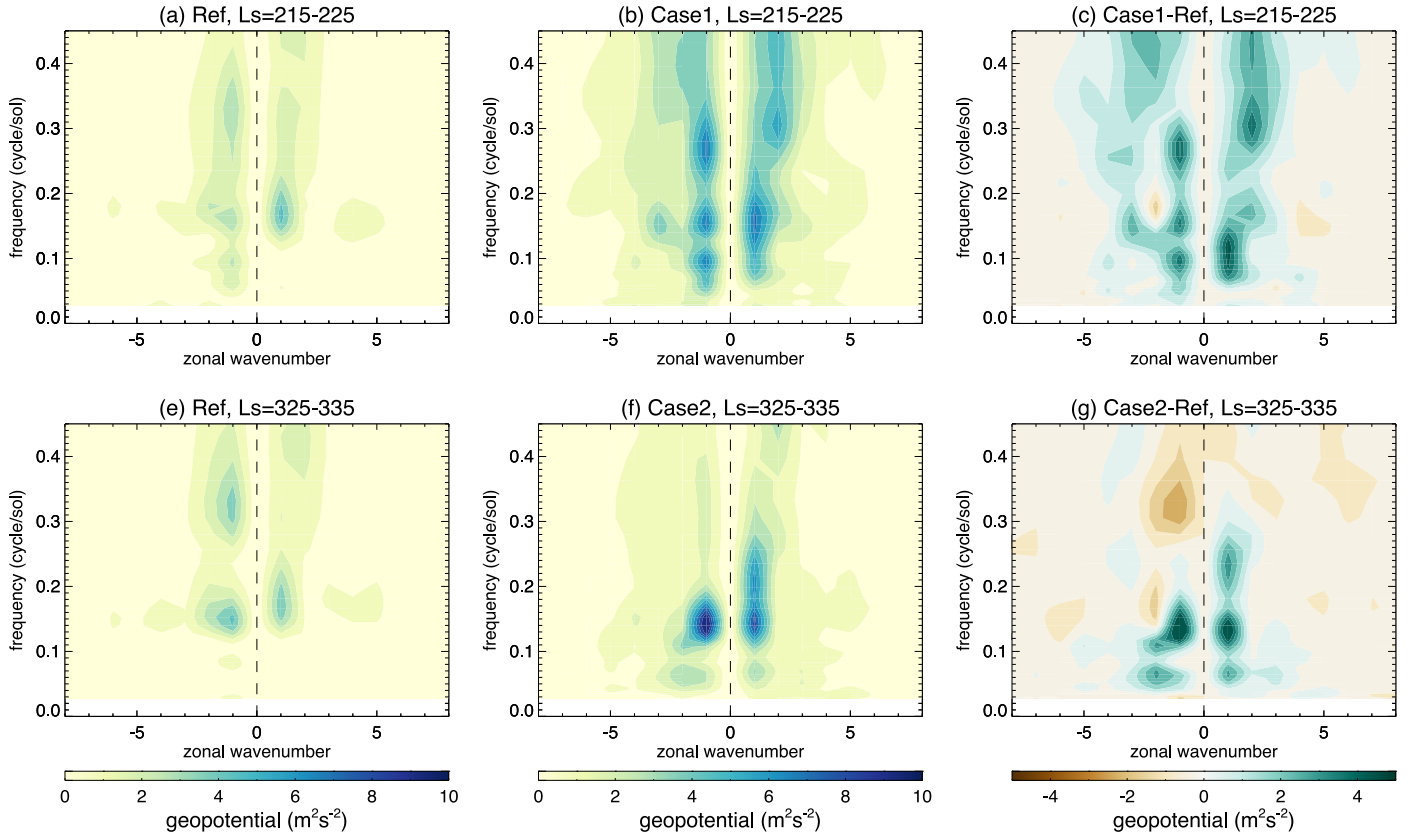
The time and zonal mean zonal winds show significant vertical and meridional shear in the tropics (Figure A4). Consequently, traveling waves with different phase speeds will encounter their critical levels (where wave phase speeds equal background wind speeds) at different heights and latitudes. For instance, a  $c = -15$   $\text{m s}^{-1}$  wave will encounter its critical level around  $z \sim 20$  km at  $10^\circ\text{S}$  and around  $z \sim 35$  km at  $10^\circ\text{N}$ .

General intensification of eastward and westward  $k = \pm 1$  to  $k = \pm 5$  waves is seen during both prescribed dust storm episodes (Figure 5). The amplification is present across a wide frequency range and is quite noticeable for low-frequency



**Figure 4.**  $L_s$ -longitude plot of eastward- (top row) and westward-propagating (bottom row) eddies with  $P = 7\text{--}30$  sols in the geopotential ( $\text{m}^2 \text{s}^{-2}$ ) field at  $p = 100$  Pa and  $1^\circ \text{S}$  for the reference (left), Case1\_MY32A (middle), and Case2\_MY33C (right) simulations. Solid lines in Case1\_MY32A and Case2\_33C plots bracket the  $L_s$  period when dust storms are added for the simulations. Dashed lines correspond to first occurrence of significant dust storm members near the equator.





**Figure 5.** Wave amplitude for  $p = 100$  Pa geopotential ( $\text{m}^2 \text{s}^{-2}$ ) as a function of wave frequency (cycles/sol) and zonal wavenumber for (a) reference run  $L_s = 215^\circ - 225^\circ$ , (b) Case1\_MY32A  $L_s = 215^\circ - 225^\circ$ , (e) reference run  $L_s = 325^\circ - 335^\circ$ , and (f) Case2\_MY33C  $L_s = 325^\circ - 335^\circ$ . Positive (negative) zonal wavenumbers correspond to eastward-propagating (westward-propagating) waves. Each spectrum is averaged between  $15^\circ\text{S}$  and  $15^\circ\text{N}$  during the corresponding  $L_s$  period. Differences between the second and first column (from left) are shown in panels (c) and (g), respectively.

( $f < 0.1$  cycles/sol), long-period ( $P > 10$  sols) waves. For Case1\_MY32A, these are primarily eastward  $k = 1$  and westward  $k = -1$  waves. For Case2\_MY33C, these are primarily eastward  $k = 1$  and westward  $k = -2$  waves. A wider range of waves are active in Figure 5(b) than in Figure 5(f), suggesting more complex behavior for eddy geopotential at 100 Pa during the modeled presolstice episode. Sometimes, waves of the same frequency but opposite propagation directions show comparable amplitudes (e.g.,  $k = \pm 1$ ,  $f \sim 0.16$  cycle/sol waves in Figure 5(b)), which suggests a standing wave possibly resulting from a dominant dust storm member in a longitudinal sector. Although intensification dominates, there are exceptions. For example, the  $k = -1$ ,  $f \sim 0.31$  cycle/sol waves and  $k = -2$ ,  $f \sim 0.17$  cycle/sol waves weaken significantly during  $L_s = 325^\circ - 335^\circ$  for Case2\_33C as compared to the reference run (Figure 5(g)). Thus, technically, both strengthening and weakening occurred depending on which waves; however, the overall trend is strengthening of a wide variety of tropical waves.

Besides the waves in the reference run, some new spectral peaks occur. Examples for  $L_s = 215^\circ - 225^\circ$  of Case1\_MY32A include  $f \sim 0.27$  cycles/sol ( $P \sim 3.7$  sols,  $c \sim -65 \text{ m s}^{-1}$ ) for  $k = -1$ ,  $f \sim 0.15$  cycles/sol ( $P \sim 6.7$  sols,  $c \sim -12 \text{ m s}^{-1}$ ) for  $k = -3$ , and  $f \sim 0.31$  cycles/sol ( $P \sim 3.2$  sols,  $c \sim 37 \text{ m s}^{-1}$ ) for  $k = 2$ , among others (Figures 5(b) and (c)). During  $L_s = 325^\circ - 335^\circ$  of Case2\_MY33C, the strong  $k = \pm 1$  peaks for  $f < 0.2$  cycles/sol occur at slightly lower frequency than those in the reference simulation, and additional peaks occur at  $f \sim 0.22$  cycles/sol ( $P \sim 4.5$  sols) for  $k = 1$  and  $f \sim 0.055$

cycles/sol ( $P \sim 18$  sols) for  $k = -2$ . Thus, it appears that changes in wave spectra depend on both the detail of dust storm forcing and time of year.

### 3.2.2. Wave Spectrum Variations

To check for interannual consistency, we repeat the spectral analysis described above, on the 100 Pa geopotential for other simulation years of the reference run and Case1\_MY32A. Results for three randomly selected pairs of years are shown in Figure A5. In comparison with Figures 5(a) and (b), the details of the relative wave amplitudes vary slightly among the years. However, the general pattern of tropical wave amplification in association with the prescribed dust storm episode remains apparent.

As waves have 3D structures and different waves could be filtered by background winds at different heights (D. P. Hinson & R. J. Wilson 2023; H. Wang et al. 2024), the wave spectrum is expected to vary vertically. We derived the wave spectra for geopotential at the  $p = 50$  Pa ( $z \sim 30$  km altitude) pressure level and the  $\eta = 0.383$  ( $h \sim 10$  km high above the surface) and  $\eta = 0.767$  ( $h \sim 3$  km) vertical model levels using the same output as those for Figures 5(a) and (b) (Figure A6). For  $p = 50$  Pa, waves within a wide frequency range are amplified. This is generally consistent with the result for  $p = 100$  Pa, though the details show some variations. For example, instead of strengthening, the  $k = 1$ ,  $f \sim 0.17$  wave weakens with respect to the reference at  $p = 50$  Pa. However, for both  $\eta$  levels that are within  $h \sim 10$  km of the surface, geopotential wave amplitudes are roughly comparable between the reference run and Case1\_MY32A for  $f > 0.1$  cycles/sol.



Those waves probably are vertically confined in the reference run and can propagate to higher altitudes during the dust storm episode. Nonetheless, amplification with respect to the reference is clearly seen for  $f < 0.1$  cycle/sol waves for both  $\eta$  levels, which could suggest that these tropical low-frequency long waves are excited near the surface by dust storms and propagate to high altitudes.

Wave amplitudes also depend on variables of interest; we thus examined the wave spectra of zonal wind ( $u$ ) at 100 Pa, meridional wind ( $v$ ) at 100 Pa, zonal wind at  $\eta = 0.383$  model level, and surface friction velocity ( $U^*$ ) in Figure 6. The spectra are derived using the same output dataset as those for Figures 5(a) and (b). In comparison with the reference, all the variables exhibit a general tendency for wave amplification, but the patterns differ. In comparison with the geopotential at 100 Pa, the spectra for  $u$  and  $v$  at 100 Pa appear to emphasize the amplification for  $f = 0.1$ – $0.3$  cycle/sol waves more, with  $v$  ( $u$ ) preferentially for westward-propagating (eastward-propagating) waves in this case (Figures 6(a)–(d)). However, due to the complexity in the vertical dimension, the preference for a particular direction is nonuniform, as  $u$  at  $\eta = 0.383$  has stronger westward wave amplification instead (Figures 6(e) and (f)). For  $f < 0.1$  cycle/sol waves,  $u$  at 100 Pa significantly strengthens, but not so much for  $v$  at 100 Pa (Figures 6(a)–(d)). This could be partially related to wave structures. For example, Kelvin waves and some Rossby waves have strong  $u$  perturbation but zero  $v$  perturbation along the equator. For surface friction velocity ( $U^*$ ), which is directly relevant to wind stress dust lifting (C. E. Newman & M. I. Richardson 2015), the wave spectra spread over a larger domain in the frequency versus zonal wavenumber space (Figures 6(g) and (h)), and the  $f < 0.1$  cycle/sol long waves are noticeably enhanced among others for Case1\_MY32A.

### 3.3. Wave Period–Time Distribution

To investigate how wave spectra evolve with time during the dust storm season, we average the spacetime spectral amplitude of the  $p = 100$  Pa geopotential between  $15^\circ\text{S}$  and  $15^\circ\text{N}$  at each time step. Figure 7 shows the result for Case1\_MY32A as a function of wave period and  $L_s$  for eastward- and westward-propagating waves with zonal wavenumbers  $k = \pm 1$  to  $\pm 4$ . The corresponding result for the reference run is shown in Figure A7.

Consistent with Figures 4(b) and (e), the waves in Figure 7 appear generally stronger in Case1\_MY32A than in the reference run during  $L_s = 215^\circ$ – $230^\circ$ . The intensified waves span a wide range of wave periods. The details differ among zonal wavenumbers and propagation directions, but all show significant changes during the  $L_s$  period when near-equator dust storms perturb the atmosphere. Consistent with the results in Figures 5(a) and (b), the intensification of relatively long period ( $P > 5$  sols) waves is particularly noticeable in Figure 7, though some with shorter wave periods are also enhanced with respect to the reference. The dust storm episode appears to have excited a broad spectrum of equatorial waves when and after it crossed the equator from the northern to the southern hemisphere.

### 3.4. Longitude–Latitude Structure

The classical equatorial wave theory (T. Matsuno 1966) predicts different families of waves (e.g., Kelvin, equatorial

Rossby, MRG, and IG) with characteristic dispersion relationships and longitude–latitude structures. As shown in Sections 3.1–3.3, a wide variety of waves are strengthened in the equatorial region during the prescribed dust storm episodes. These waves interfere with each other and change amplitudes with time. Consequently, the longitude–latitude snapshots of the total eddy field are complex and time dependent.

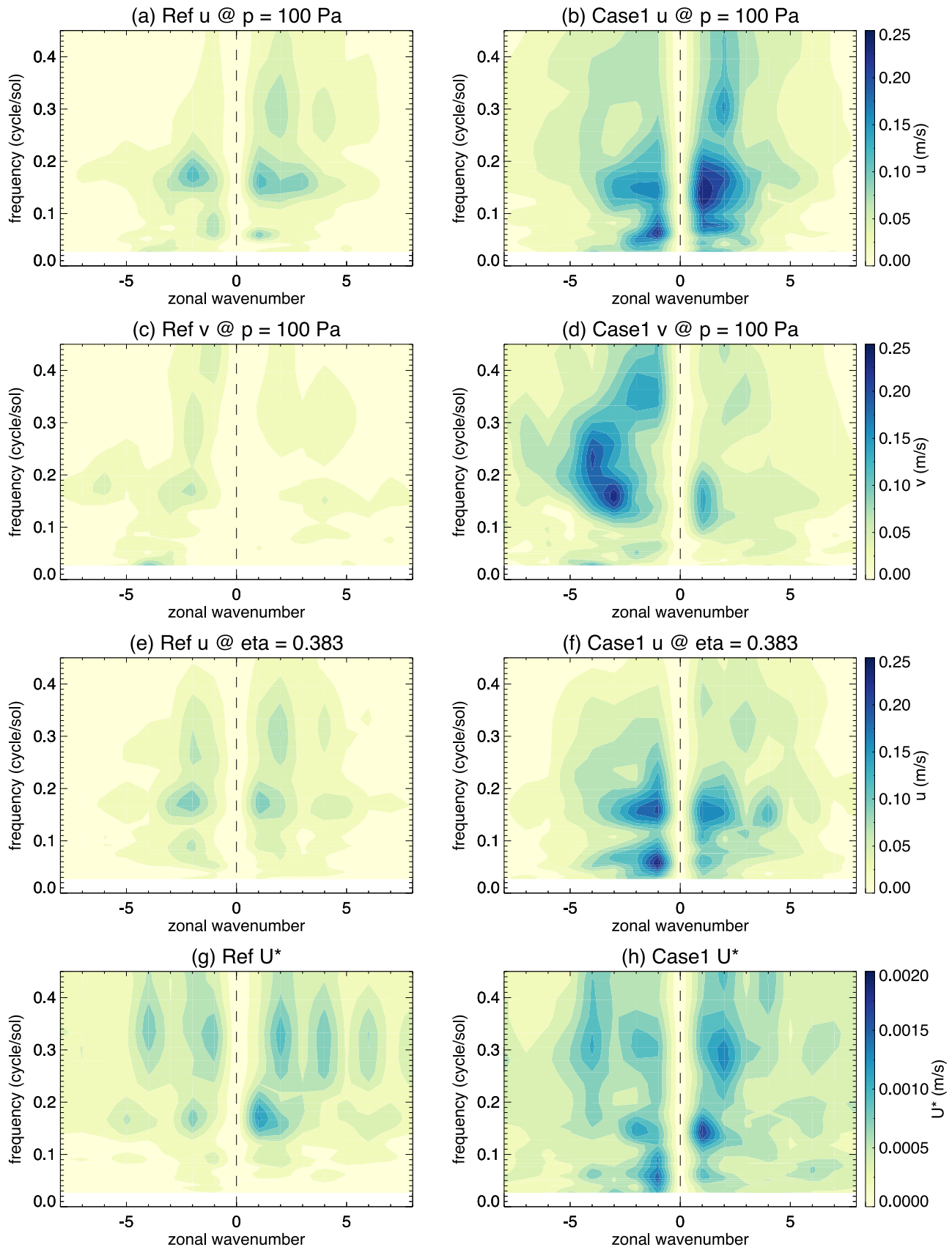
Figure 8 shows the horizontal structures of the  $p = 100$  Pa eddy geopotential at a moment when strong waves are seen in Figures 4(b) and (e) ( $L_s \sim 223^\circ$ ). Eastward- and westward-propagating components are shown separately along with their first three zonal wavenumbers. Each panel includes contributions from  $P = 1.7$ – $60$  sol waves. Thus, the structure shown is not for any single wave. However, at times, the eddy field can be dominated by one.

The eastward  $k = 1$  panel (Figure 8(c)) shows a peak geopotential amplitude near the equator and decays toward higher latitudes with a half-width of about  $12^\circ$  latitude. When decomposed into a symmetric component and an antisymmetric component with respect to the equator, the meridional wind associated with the symmetric geopotential is negligible near the equator, which is reminiscent of a Kelvin wave, while the meridional wind associated with the antisymmetric geopotential is significant across the equator, which is suggestive of an IG wave. The westward  $k = -1$  panel (Figure 8(d)) shows a minimal geopotential amplitude along the equator and two off-equator maxima near  $15^\circ\text{N/S}$ . A similar structure is shown by the westward  $k = -2$  panel (Figure 8(f)). This type of structure could be that of an equatorial Rossby wave with a meridional wave mode number  $n = 1$  (T. Matsuno, 1966). The eastward  $k = 2$  and  $k = 3$  panels suggest off-equator maxima in geopotential with significant antisymmetry about the equator (Figures 8(e) and (g)). This type of structure could be an ( $n = 0$ ) MRG or an IG wave (T. Matsuno, 1966).

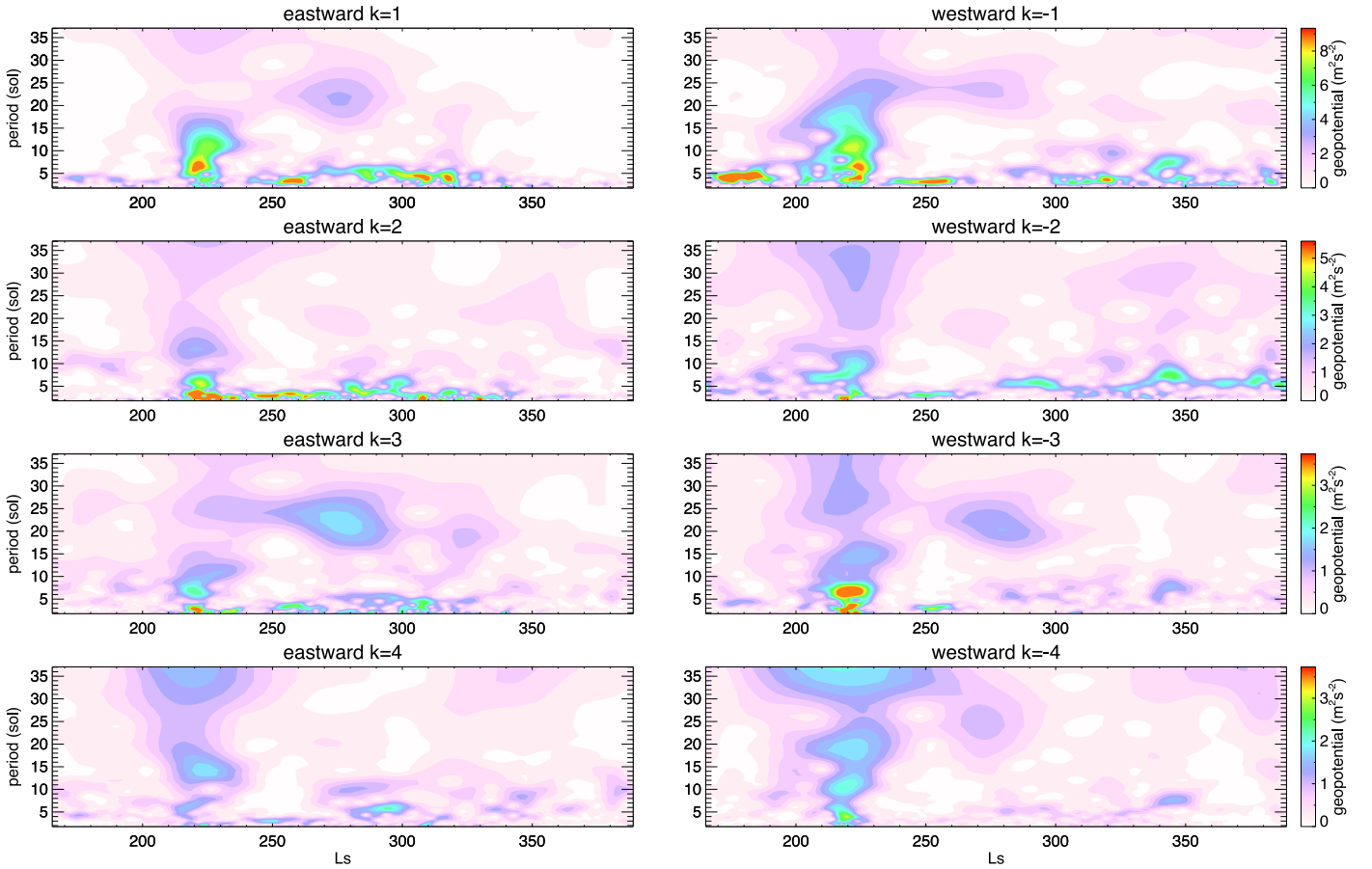
The wave structures in Figure 8 are not strictly symmetric or antisymmetric about the equator and often tilt with latitude, which deviates from the theoretical solutions of T. Matsuno (1966). As each panel contains multiple waves possibly characterized by different meridional modes with different phase speeds, other waves could interfere with the dominant wave, leading to an altered horizontal wave pattern. Additionally, background winds strongly influence wave structures and propagations (G.-Y. Yang et al. 2003; P. J. Webster 2020). The model winds show substantial meridional and vertical shear (Figure A4), which is much more complex than the idealized theoretical assumption of zero wind. This will also lead to modifications in wave structure. Despite the complications, Figure 8 suggests some essential characteristics of various types of equatorial waves when dust storms perturb the tropical atmosphere.

### 3.5. Sensitivity Tests

Exp1\_Acidalia32A and Exp2\_Acidalia32C are both forced by the imposition of the Acidalia sequence of dust storm evolution (Section 2.2) but during different  $L_s$  periods. We construct their Hovmöller diagrams for eastward- and westward-propagating eddies in the  $p = 100$  Pa geopotential field at  $1^\circ\text{S}$  (Figure A8). For both experiments, comparisons with the reference show that apparent changes in wave properties occur about  $10^\circ$  of  $L_s$  after the start of Acidalia sequence. The



**Figure 6.** Wave amplitude as a function of wave frequency (cycles/sol) and zonal wavenumber for the reference run (left column) and Case1\_MY32A (right column) for (a, b)  $u$  (m s<sup>-1</sup>) at 100 Pa, (c, d)  $v$  (m s<sup>-1</sup>) at 100 Pa, (e, f)  $u$  (m s<sup>-1</sup>) at  $\eta = 0.383$  model level, and (g, h) surface friction velocity  $U^*$  (m s<sup>-1</sup>). Positive (negative) zonal wavenumbers correspond to eastward-propagating (westward-propagating) waves.



**Figure 7.** Wave amplitude of  $p = 100$  Pa geopotential ( $\text{m}^2 \text{s}^{-2}$ ) averaged between  $15^\circ\text{S}$  and  $15^\circ\text{N}$  as a function of wave period (sol) and  $L_s$  for Case1\_MY32A. Panels from top to bottom are for zonal wavenumbers  $k = \pm 1$  to  $k = \pm 4$ . Left and right columns are for eastward- and westward-propagating waves, respectively.

timing coincides with the occurrence of near-equatorial dust storm members. This is consistent with the indication from Figure 4 that significant perturbations to the equatorial atmosphere and excitation of waves occur once the dust storm sequence crosses the equator (after the dashed lines).

Figure 9 shows the Hovmöller diagrams for eastward- and westward-propagating  $P = 7$ – $30$  sol eddies in the  $p = 100$  Pa geopotential field at  $1^\circ\text{S}$  for the Climatology32, Scaled32, and Climatology33 runs. Despite the same global mean dust optical depth on each sol, Climatology32 and Scaled32 have very different equatorial waves. In comparison, Climatology32 and Climatology33 differ in both global mean dust (Figure A3) and dust storm episodes (H. Wang et al. 2023a). Yet the waves in Climatology32 have more similarity to those in Climatology33 than those in Scaled32. This suggests that perturbations associated with dust storm members strongly influence the behaviors of equatorial waves.

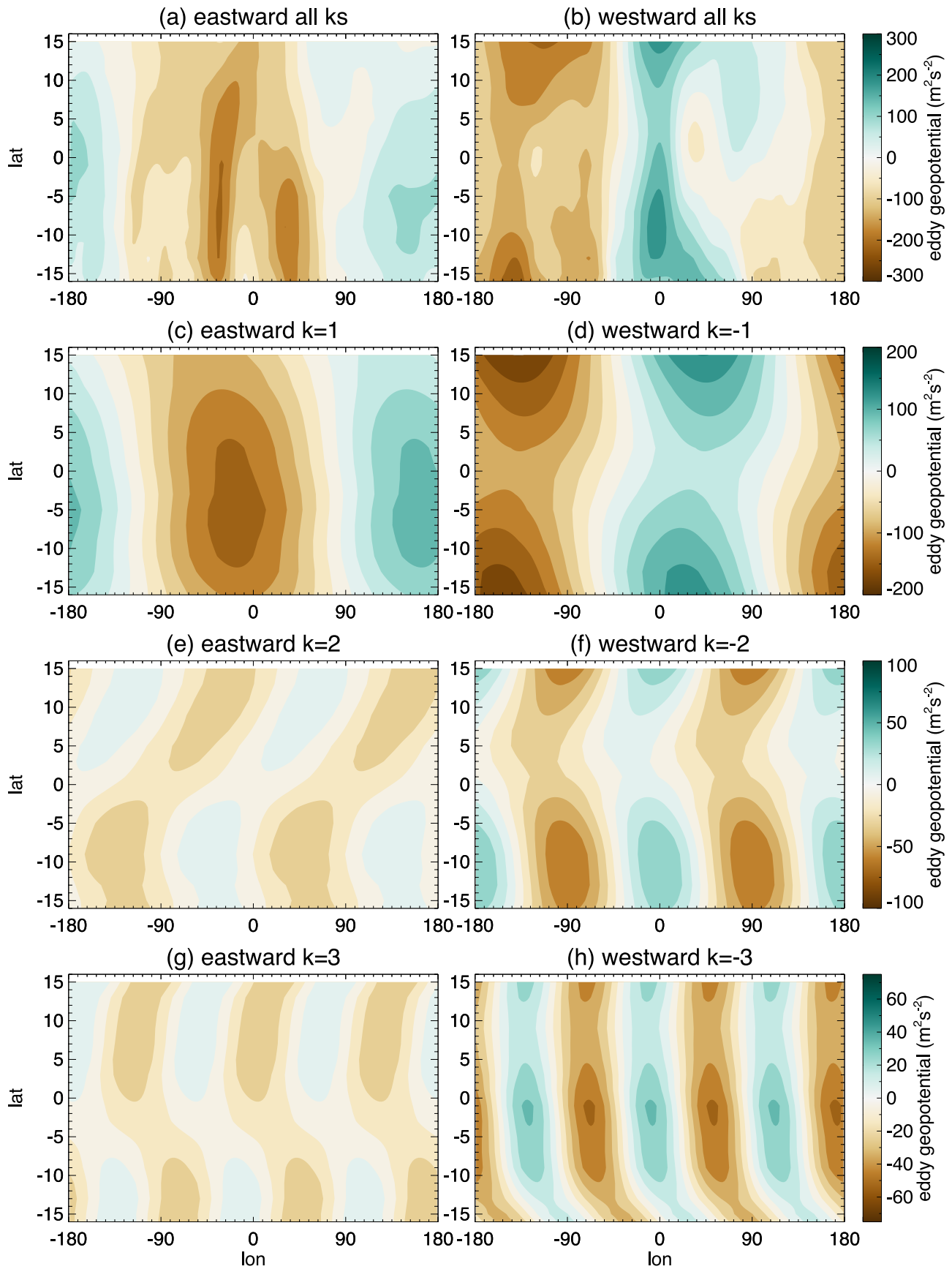
A closer inspection of Figure 9 shows that the details of equatorial waves differ between Climatology32 and Climatology33. For instance, near  $L_s = 330^\circ$ , relatively fast-moving eastward waves (as suggested by shallower slopes with respect to the horizontal axis) are noticeable in Climatology32, but they appear to have dissipated earlier in Climatology33. For  $L_s = 180^\circ$ – $210^\circ$ , in comparison with Scaled32, the eastward  $k = 1$  wave for Climatology33 appears to be enhanced earlier than that for Climatology32; however, the westward waves for Climatology32 exhibit significant enhancement throughout  $L_s = 180^\circ$ – $210^\circ$ , while those for Climatology33 show much less or no obvious enhancement. The discrepancies suggest

that equatorial waves are sensitive to how different dust storm episodes perturb the Martian atmosphere.

For Scaled32, apparent changes in the amplitudes and propagation speeds of equatorial waves are seen during  $L_s = 210^\circ$ – $240^\circ$  (Figures 9(b) and (e)), which corresponds to a period of rapidly increasing global mean dust optical depth (Figure A3). Although there are slight variations in the spatial distributions of background dust from sol to sol owing to how the no\_storm dust scenario was constructed (H. Wang et al. 2023b), there are no imposed dust storm instances. During  $L_s = 215^\circ$ – $225^\circ$  when Figure 9 shows highly regular traveling waves for Scaled32, the spacetime spectrum for  $15^\circ\text{S}$ – $15^\circ\text{N}$  is dominated by an eastward-propagating  $k = 1$  wave with  $P \sim 9$  sols ( $c \sim 26 \text{ m s}^{-1}$ ), with the wave structure suggesting a combination of Kevin and IG waves. The increasingly dustier atmosphere is associated with significant changes in background winds upon which waves propagate and dissipate. Thus, besides direct perturbations from dust storm episodes, apparent changes in equatorial waves can also occur when the global background dust opacity varies.

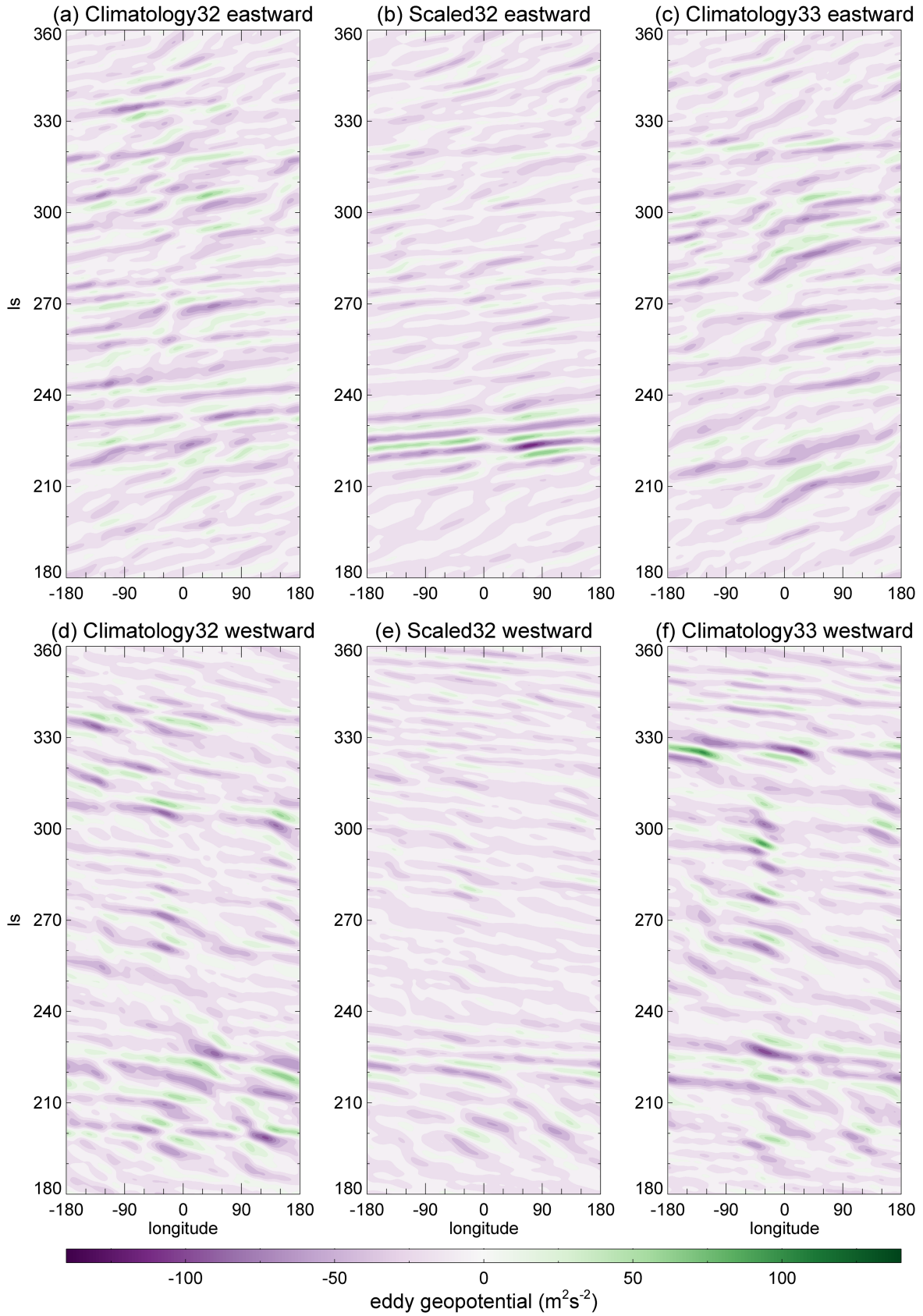
#### 4. Summary

The tropical atmospheric circulation plays an essential role in the Martian water and dust cycles. Besides thermal tides, various types of equatorial waves have been derived from observations and are suggested to play significant roles in atmospheric variability. For the southern spring and summer dust storm season, tropical long waves may influence



**Figure 8.** Eddy geopotential ( $\text{m}^2 \text{s}^{-2}$ ) at  $p = 100$  Pa as a function of latitude and longitude for a time step near  $L_s = 223^\circ$  of Case1\_32A. Eastward-propagating (westward-propagating) waves are shown in the left (right) column. Rows from top to bottom are for (a, b) all zonal wavenumbers, (c, d)  $k = \pm 1$ , (e, f)  $k = \pm 2$ , and (g, h)  $k = \pm 3$  traveling waves, respectively.





**Figure 9.**  $L_s$ -longitude plot of eastward- (top row) and westward-propagating (bottom row)  $P = 7$ – $30$  sol eddies in the  $p = 100$  Pa geopotential ( $\text{m}^2 \text{s}^{-2}$ ) field at  $1^\circ\text{S}$  for Climatology32 (left column), Scaled32 (middle column), and Climatology33 (right column).

teleconnection patterns and therefore have implications about the growth mechanism of dust storms (e.g., L. Montabone et al. 2008; O. Martinez-Alvarado et al. 2009; T. A. Mooring & R. J. Wilson 2015). Using the MarsWRF GCM, this paper investigates the responses of equatorial waves to perturbations associated with various dust scenarios inspired by observed dust storm episodes.

Several simulations are conducted. Each is driven by a prescribed dust scenario. When prescribed dust storm members cross the equator, noticeable changes are seen in the spacetime spectra of equatorial waves. The changes appear to depend on the timing and distribution of dust storm members, as well as on the time of year when a dust storm episode occurs. The details of spectral change vary in the vertical dimension and depend on the variables of interest; however, the amplification of a wide range of waves is seen in general. It appears that the waves may yield information on how dust storm episodes develop as they perturb the tropical Martian atmosphere through different trajectories and in different seasons.

Many waves are strengthened in the perturbed tropical atmosphere, especially waves with low frequency and long wavelength. These waves may spread perturbations due to dust storms around the tropics in tens of days, consistent with occurrence of subsequent dust lifting center onset in observed global dust storms (e.g., M. J. Strausberg et al. 2005). The derived wave structures suggest some characteristic features of various types of equatorial waves, such as Kelvin wave, equatorial Rossby wave, IG wave, and MRG wave.

Sensitivity tests show that significant changes in equatorial waves can also occur when the background dust optical depth varies without any prescribed dust storm episode. This is probably related to changes in simulated winds that affect the structure and propagation of equatorial waves (P. J. Webster 2020). Thus, a dust storm could be a sufficient but not necessary condition for changes in equatorial waves.

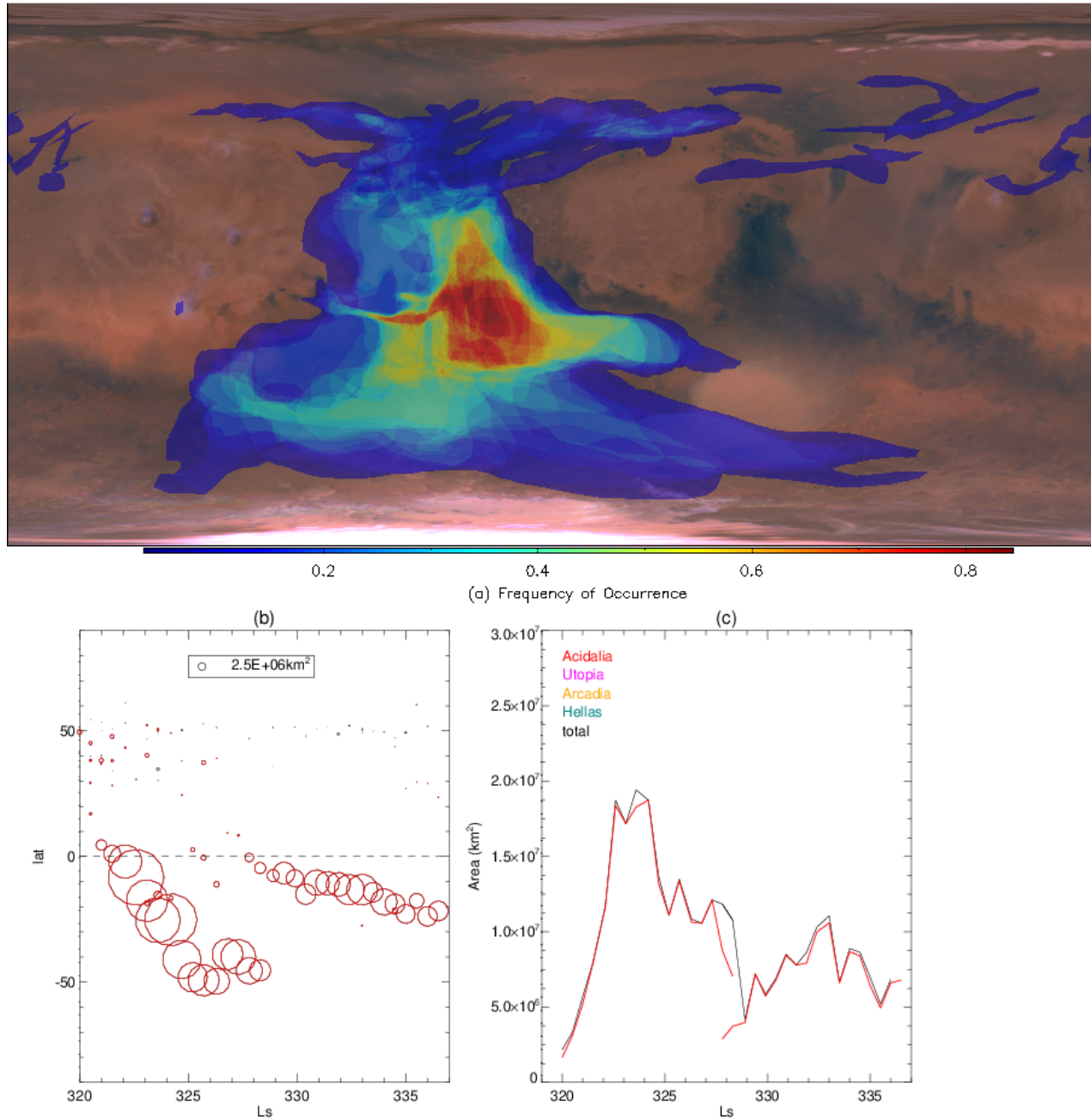
This study recognizes a complex relationship among equatorial waves, background dust, and dust storm episodes in the Martian atmosphere. Future work will systematically study their connections. Equatorial waves provide a mechanism for tropical atmospheric variability on timescales of days to tens of days, and for disturbances in one part of the tropics to influence other locations around the globe. Better understanding of these waves is valuable for advancing the understanding of the Martian atmosphere.

### Acknowledgments

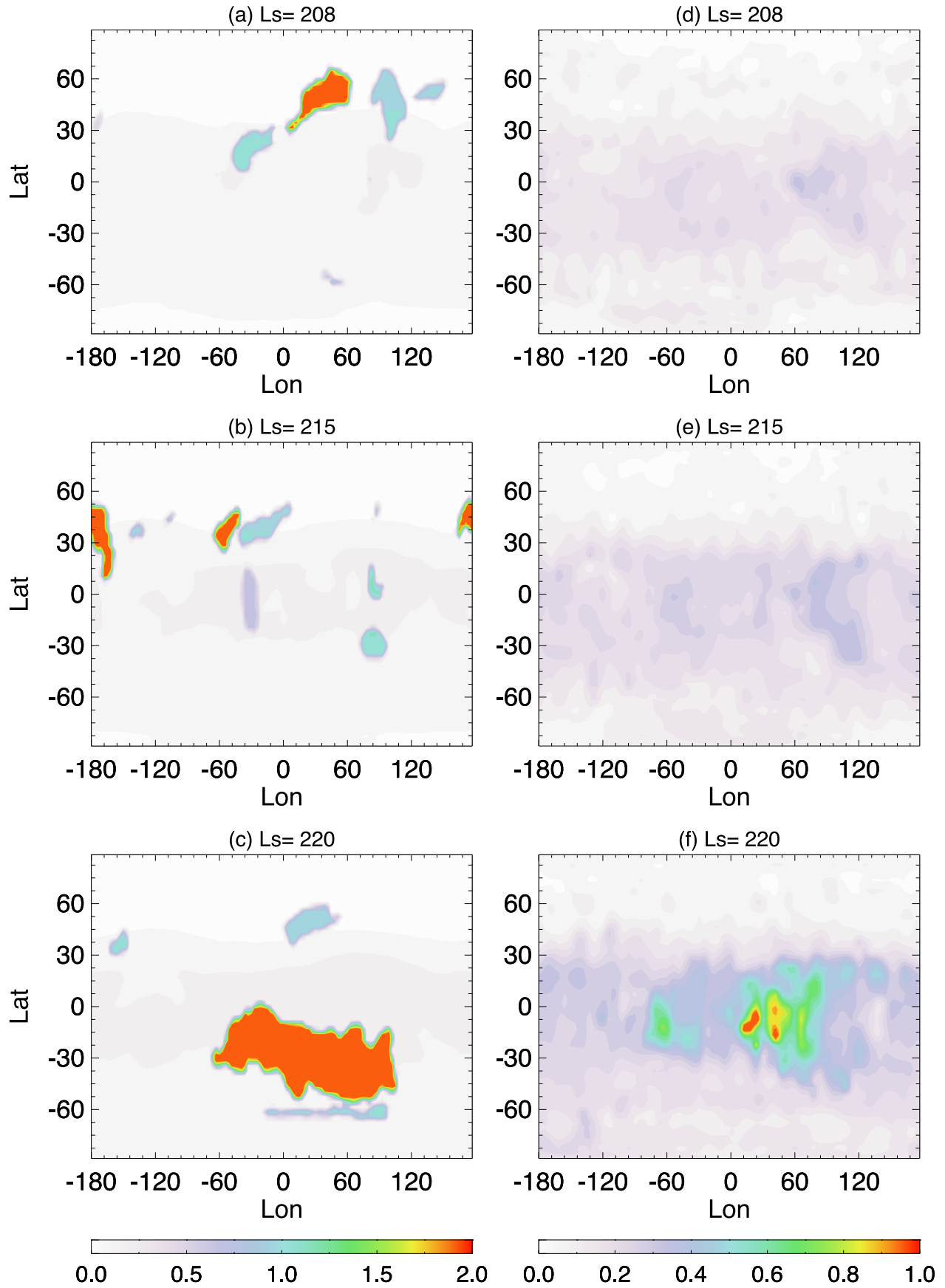
Support for this project is provided by NASA grants 80NSSC21K1831 and 80NSSC23K1077. Computational resources supporting this work were provided by the NASA High-End Computing (HEC) program through the NASA Advanced Supercomputing (NAS) division at Ames Research Center. Supporting material for this paper can be accessed at Harvard Dataverse [10.7910/DVN/UPYTEU](https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/UPYTEU). We thank two anonymous reviewers for their suggestions to improve this paper.

## Appendix Supplementary Figures

This Appendix contains supplementary Figures A1–A8 and their captions.

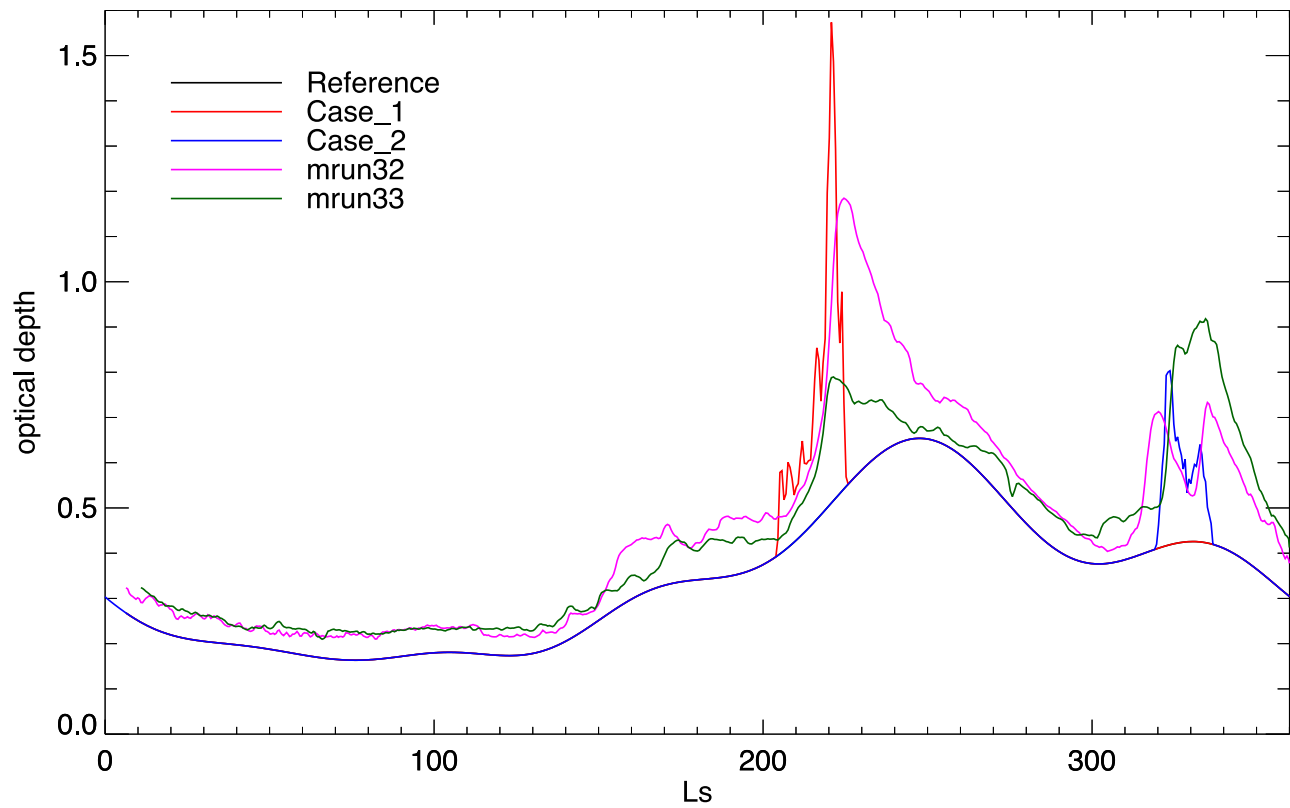


**Figure A1.** Dust storm episode during  $L_s = 320^\circ$ – $335^\circ$  of MY33. (a) Latitude–longitude distribution of storm occurrence frequency as illustrated by storm occurrence frequency during the  $L_s$  interval. (b) Latitude– $L_s$  distribution of the centroids of dust storm members. Symbol sizes are proportional to storm areas. Symbol colors have the same meanings as those in panel (c). (c) Area ( $km^2$ ) as a function of  $L_s$  during the episode. Color keys indicate the origination regions of dust storm sequences. The black line corresponds to the sum of all dust storm sequences.

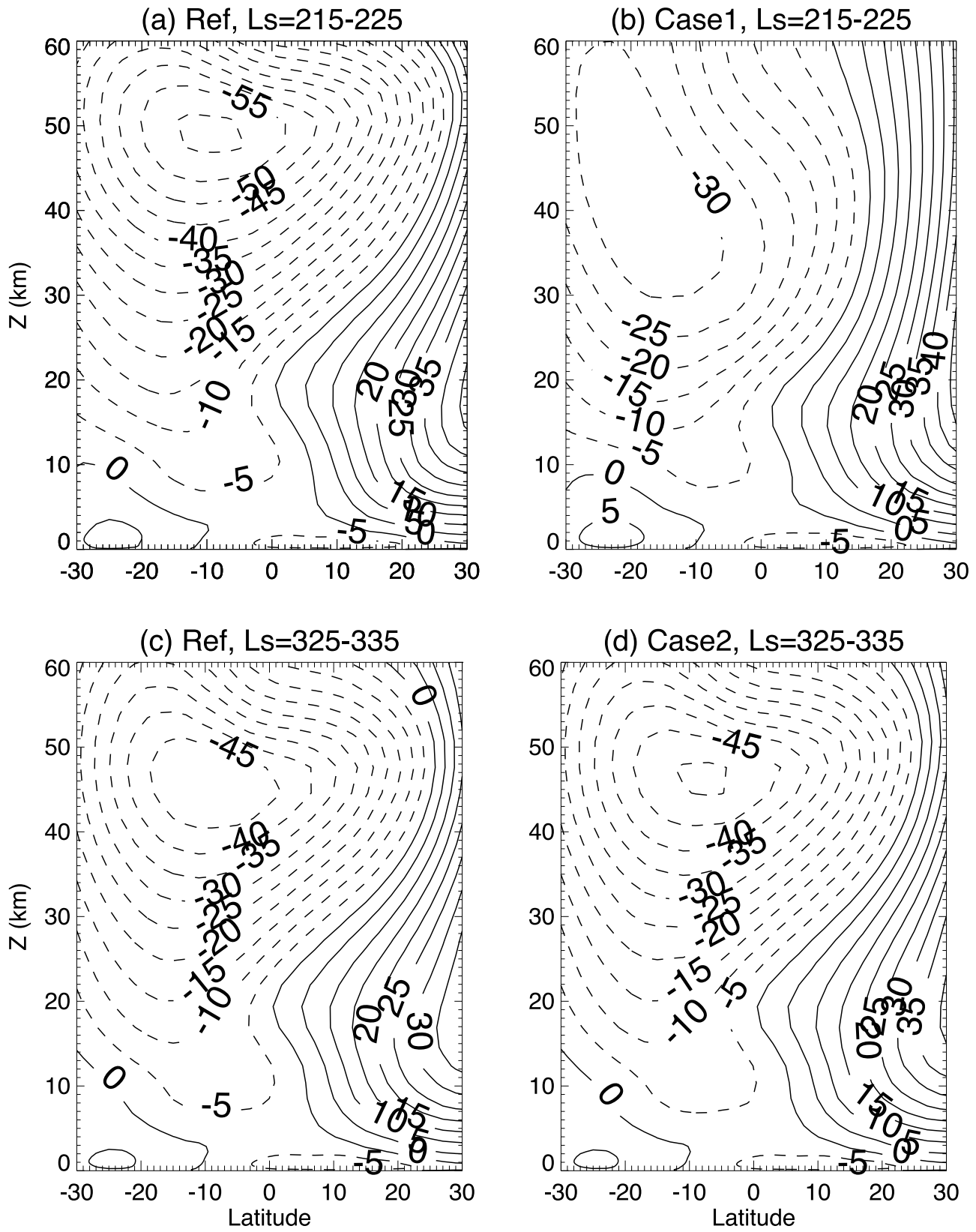


**Figure A2.** Latitude-longitude distribution of 9.3  $\mu\text{m}$  absorption dust optical depth (scaled to 610 Pa) at (a, d)  $L_s = 208^\circ$ , (b, e)  $L_s = 215^\circ$ , and (c, f)  $L_s = 220^\circ$  prescribed for (a-c) Case1\_MY32A and (d-f) Climatology32. For panels (a)-(c), the background dust is from the “no\_storm” dust scenario. The imposed dust storm members are from the dust storm episode during  $L_s = 205^\circ$ – $225^\circ$  of MY32 in MDSSD. For panels (d)-(f), the MY32 climatology of L. Montabone et al. (2015) is plotted.

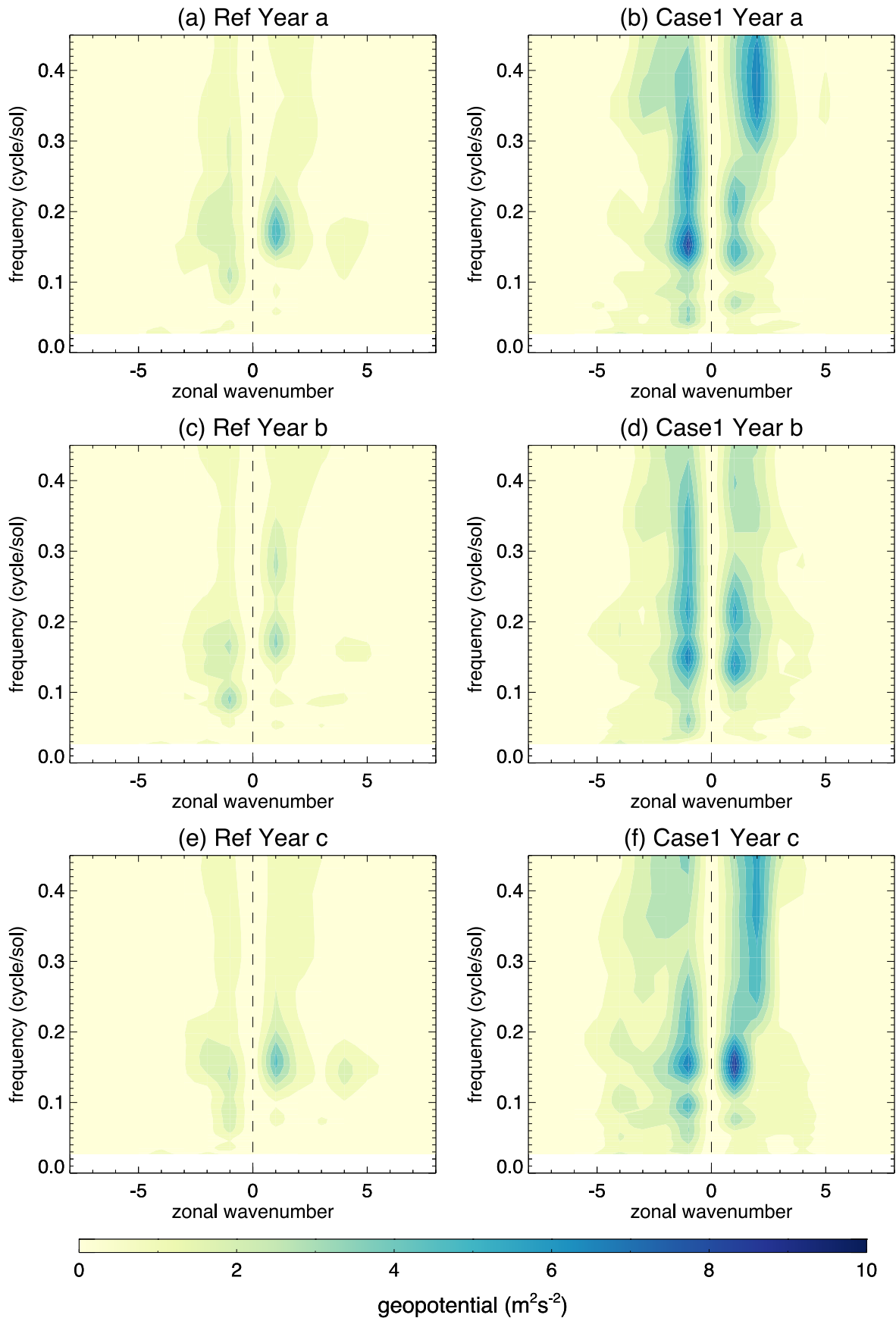




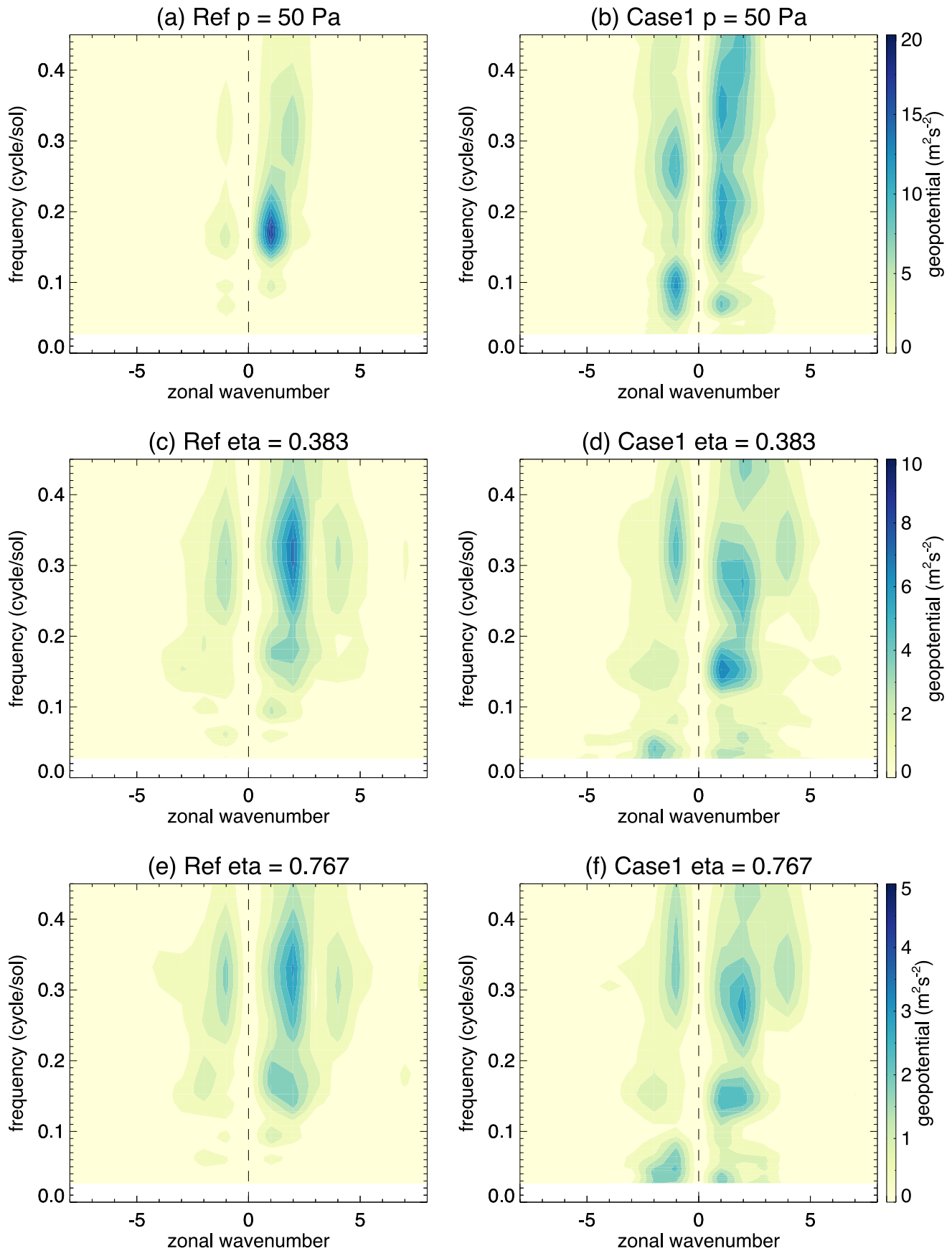
**Figure A3.** Globally averaged dust optical depth CDOD610 (as defined in L. Montabone et al. 2015) as a function of  $L_s$  for reference (black), Case1\_MY32A (red), Case2\_MY33C (blue), MY32 climatology (magenta), and MY33 climatology (green), as listed in Table 1 of the main text.



**Figure A4.** Altitude (Z, km) vs. latitude (degree) cross sections of zonal mean zonal wind ( $\text{m s}^{-1}$ ) averaged within (a, b)  $L_s = 215^\circ\text{--}225^\circ$  and (c, d)  $L_s = 325^\circ\text{--}335^\circ$  for the (a, c) reference, (b) Case1\_AcidaliaA, and (d) Case2\_AcidaliaC simulations.

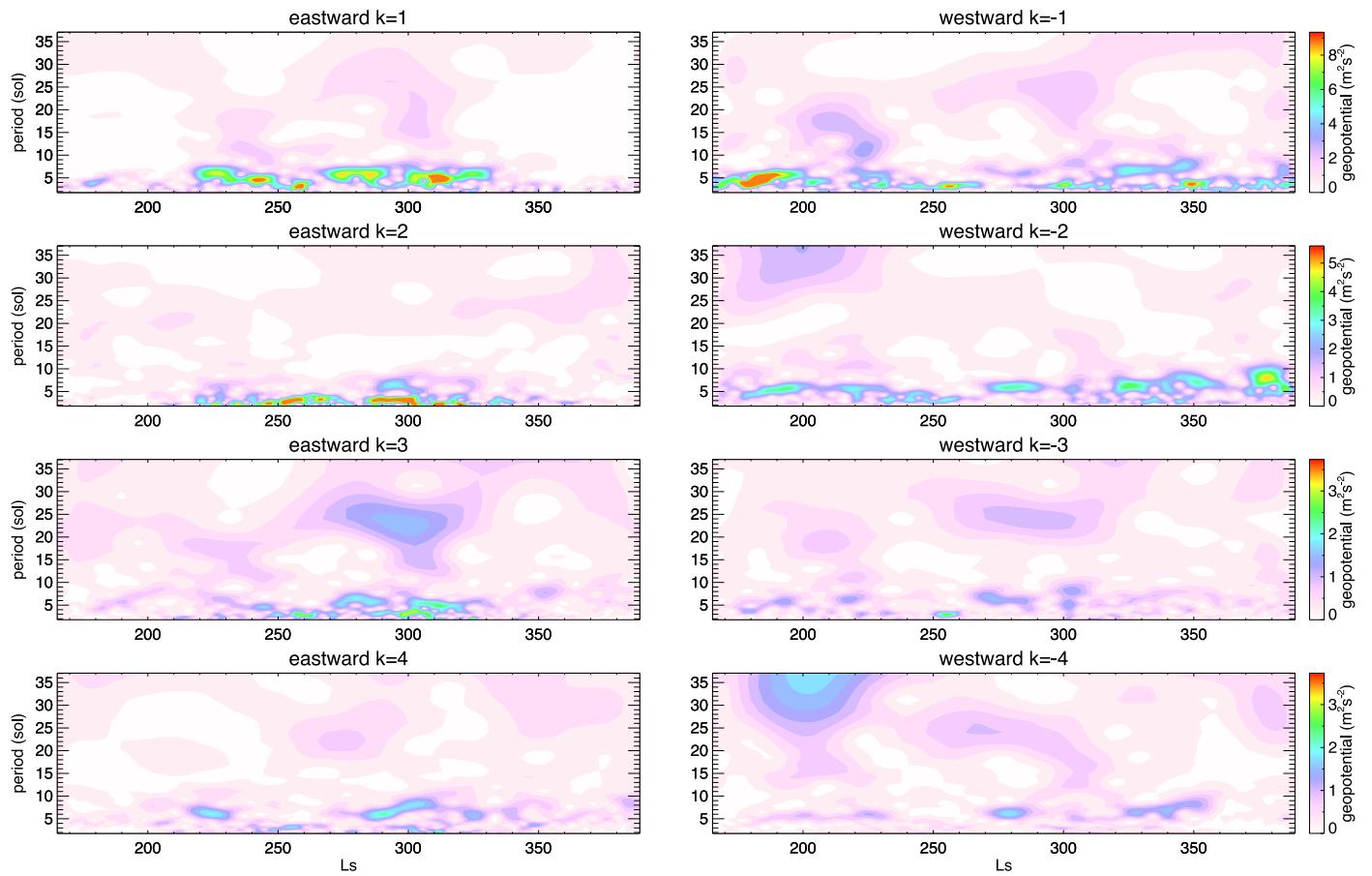


**Figure A5.** Wave amplitude for  $p = 100$  Pa geopotential ( $\text{m}^2 \text{s}^{-2}$ ) as a function of wave frequency (cycles/sol) and zonal wavenumber for the reference run (left column) and Case1\_MY32A run (right column) for (a, b) Year a, (c, d) Year b, and (e, f) Year c. Positive (negative) zonal wavenumbers correspond to eastward-propagating (westward-propagating) waves. Each spectrum is averaged between  $15^\circ\text{S}$  and  $15^\circ\text{N}$  during  $L_s = 215^\circ\text{--}225^\circ$ . Results are for comparison with Figures 5(a) and (b).

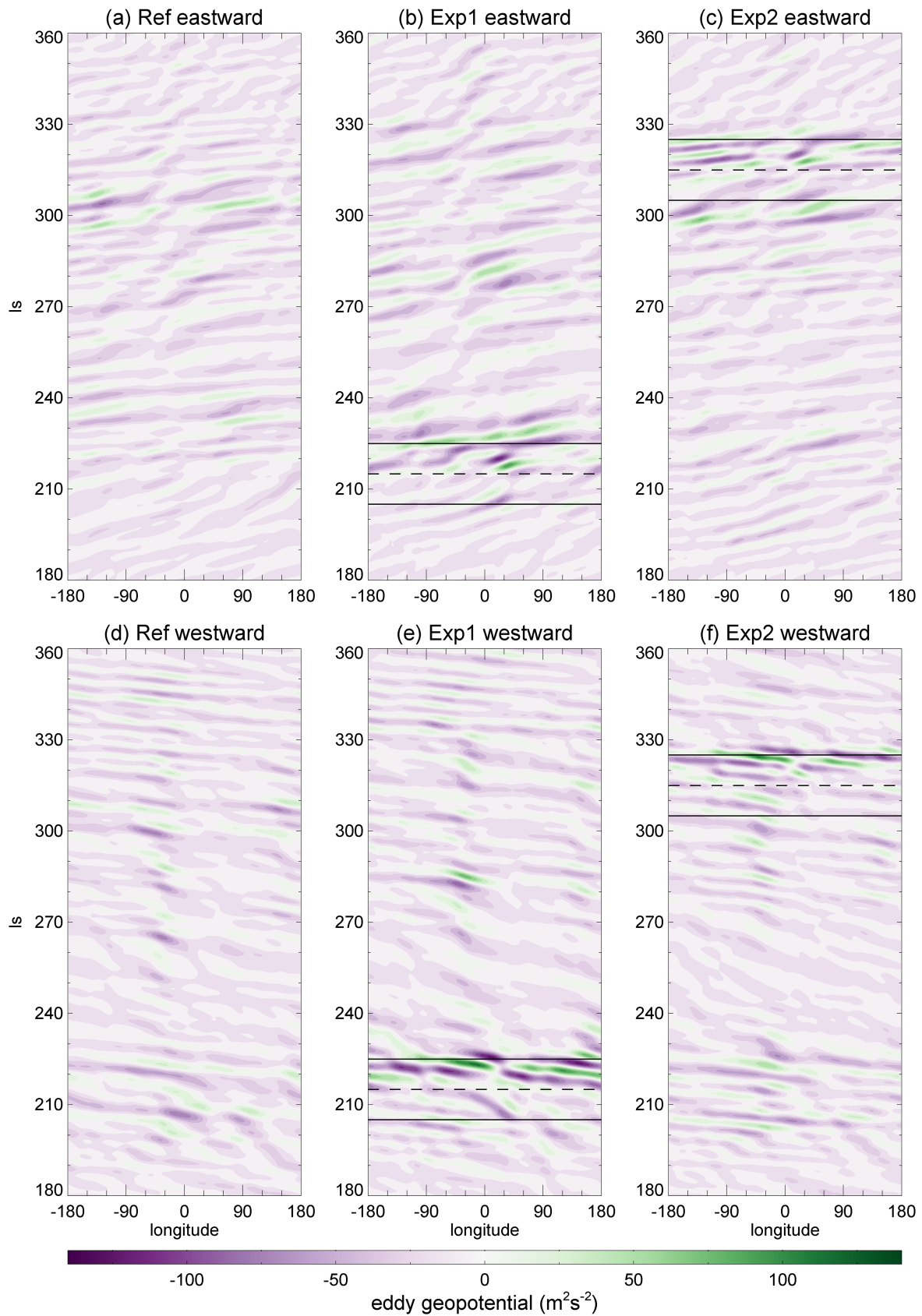


**Figure A6.** Geopotential wave amplitude ( $\text{m}^2 \text{s}^{-2}$ ) as a function of wave frequency (cycles/sol) and zonal wavenumber for the reference run (left column) and Case1\_MY32A run (right column) for (a, b)  $p = 50 \text{ Pa}$  ( $Z \sim 30 \text{ km}$ ), (c, d)  $\eta = 0.383$  ( $h \sim 10 \text{ km}$ ), and (e, f)  $\eta = 0.767$  ( $h \sim 3 \text{ km}$ ). Note the differences in color bar scales. Positive (negative) zonal wavenumbers correspond to eastward-propagating (westward-propagating) waves. Each spectrum is averaged between  $15^\circ\text{S}$  and  $15^\circ\text{N}$  during  $L_s = 215^\circ\text{--}225^\circ$  of the same year as Figure 5.





**Figure A7.** Wave amplitude of  $p = 100$  Pa geopotential ( $\text{m}^2 \text{s}^{-2}$ ) averaged between  $15^\circ\text{S}$  and  $15^\circ\text{N}$  as a function of wave period (sol) and  $L_s$  for the reference run. Left and right columns are for eastward- and westward-propagating waves, respectively. Panels from top to bottom are for zonal wavenumber from 1 to 4, respectively.



**Figure A8.**  $L_s$ -longitude plot of eastward- (top row) and westward-propagating (bottom row) waves with wave periods of  $P = 7-30$  sols in the  $p = 100$  Pa geopotential ( $\text{m}^2 \text{s}^{-2}$ ) field at  $1^\circ\text{S}$  for the reference (left), Exp1\_Acidalia32A (middle), and Exp2\_Acidalia32C (right) runs. Solid lines bracket the  $L_s$  period when dust storms are superposed. Dashed lines correspond to occurrence of dust storm members near the equator.

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## References

- Banfield, D., Conrath, B. J., Gierasch, P. J., Wilson, R. J., & Smith, M. D. 2004, Traveling Waves in the Martian Atmosphere from MGS TES Nadir Data, *Icar*, **170**, 365
- Banfield, D., Spiga, A., Newman, C. E., et al. 2020, The Atmosphere of Mars as Observed by Insight, *NatGe*, **13**, 190
- Barnes, J. R., Haberle, R. M., Wilson, R. J., et al. 2017, The Global Circulation, The Atmosphere and Climate of Mars., ed. R. M. Haberle & et al., Vol. 2017 (Cambridge Univ. Press), 229
- Battalio, J. M. 2022, Transient Eddy Energetics on Mars in Three Reanalysis Datasets, *JAtS*, **79**, 361
- Battalio, J. M., Martinez, G., Newman, C. E., et al. 2022, Planetary Waves Traveling between Mars Science Laboratory and Mars 2020, *GeoRL*, **49**, 21
- Battalio, J. M., & Wang, H. 2020, Eddy Evolution during Large Dust Storms, *Icar*, **338**, 113507
- Battalio, J. M., & Wang, H. 2021, The Mars Dust Activity Database (MDAD): A Comprehensive Statistical Study of Dust Storm Sequences, *Icar*, **354**, 114059
- Bridgman, H. A., & Oliver, J. E. 2014, The Global Climate System: Patterns, Processes, and Teleconnections (Cambridge Univ. Press)
- Cantor, B. A. 2007, MOC Observations of the 2001 Mars Planet-Encircling Dust Storm, *Icar*, **186**, 60
- Clancy, R. T., & Lee, S. W. 1991, A New Look at Dust and Clouds in the Mars Atmosphere: Analysis of Emission-Phase-Function Sequences from Global Viking IRTM Observations, *Icar*, **93**, 135
- Enfield, D. B. 1989, El Niño, Past and Present, *RvGeo*, **27**, 159
- Greybush, S. J., Gillespie, H. E., & Wilson, R. J. 2019, Transient Eddies in the TES/MCS Ensemble Mars Atmosphere Reanalysis System (EMARS), *Icar*, **317**, 158
- Guzewich, S. D., Wilson, R. J., McConnochie, T. H., et al. 2014, Thermal Tides during the 2001 Martian Global-Scale Dust Storm, *JGRE*, **119**, 506
- Haberle, R. M., Pollack, J. B., Barnes, J. R., Schaeffer, J., et al. 1993, Mars Atmospheric Dynamics as Simulated by the NASA Ames General Circulation Model: 1. The Zonal-Mean Circulation, *JGRE*, **98**, 3093
- Hinson, D. P. 2025, Climatology of Transient Eddies and Dust Storms in the Southern Hemisphere of Mars, *Icar*, **436**, 116581
- Hinson, D. P., Smith, M. D., & Conrath, B. J. 2004, Comparison of Atmospheric Temperatures Obtained through Infrared Sounding and Radio Occultation by Mars Global Surveyor, *JGRE*, **109**, E12002
- Hinson, D. P., Wang, H., & Smith, M. D. 2012, A Multi-year Survey of Dynamics near the Surface in the Northern Hemisphere of Mars: Short-Period Baroclinic Waves and Dust Storms, *Icar*, **219**, 307
- Hinson, D. P., & Wilson, R. J. 2021, Baroclinic Waves in the Northern Hemisphere of Mars as Observed by the MRO Mars Climate Sounder and the MGS Thermal Emission Spectrometer, *Icar*, **357**, 114152
- Hinson, D. P., & Wilson, R. J. 2023, Diurnal Waves Forced by Horizontal Convergence of Near-Surface Winds on Mars, *Icar*, **394**, 115420
- Hinson, D. P., & Wilson, R. J. 2024, Dust-Storm Forcing of Rossby Waves on Mars, *Icar*, **412**, 115998
- Holmes, J. A., Lewis, S. R., & Patel, M. R. 2020, OpenMARS: A Global Record of Martian Weather from 1999–2015, *P&SS*, **188**, 104962
- Kahre, M. A., Murphy, J. R., & Haberle, R. M. 2006, Modeling the Martian Dust Cycle and Surface Dust Reservoirs with the NASA Ames General Circulation Model, *JGRE*, **111**, E06008
- Kahre, M. A., Murphy, J. R., Newman, C. E., et al. 2017, The Mars Dust Cycle, Atmosphere and Climate of Mars, ed. R. M. Haberle et al. (Cambridge Univ Press), 295
- Kass, D. M., Kleinböhl, A., McCleese, D. J., Schofield, J. T., & Smith, M. D. 2016, Interannual Similarity in the Martian Atmosphere during the Dust Storm Season, *GeoRL*, **43**, 6111
- Kleinböhl, A., Friedson, A. J., & Schofield, J. T. 2017, Two-Dimensional Radiative Transfer for the Retrieval of Limb Emission Measurements in the Martian Atmosphere, *JQSRT*, **187**, 511
- Kleinböhl, A., Schofield, J. T., Kass, D. M., et al. 2009, Mars Climate Sounder Limb Profile Retrieval of Atmospheric Temperature, Pressure, and Dust and Water Ice Opacity, *JGRE*, **114**, E10006
- Liu, Y., Liang, X. S., & Weisberg, R. H. 2007, Rectification of the Bias in the Wavelet Power Spectrum, *JAIOT*, **24**, 2093
- Martinez-Alvarado, O., Montabone, L., Lewis, S. R., Moroz, I. M., & Read, P. L. 2009, Transient Teleconnection Event at the Onset of a Planet-Encircling Dust Storm on Mars, *AnGp*, **27**, 3663
- Matsuno, T. 1966, Quasigeostrophic Motions in the Equatorial Area, *J. Meteor. Soc. Japan. Ser. II*, **44**, 25
- Mischna, M. A., Lee, C., & Richardson, M. I. 2012, Development of a Fast, Accurate Radiative Transfer Model for the Martian Atmosphere, Past and Present, *JGRE*, **117**, E10009
- Montabone, L., et al. 2008, Teleconnection in the Martian Atmosphere during the 2001 Planet-Encircling Dust Storm, in Mars Atmosphere: Modeling and Observations Workshop, 9077 (Virginia, USA)
- Montabone, L., Forget, F., Millour, E., et al. 2015, Eight-Year Climatology of Dust Optical Depth on Mars, *Icar*, **251**, 65
- Mooring, T. A., & Wilson, R. J. 2015, Transient Eddies in the MACDA Mars Reanalysis, *JGRE*, **120**, 1671
- Mulholland, D. P., Read, P. L., & Lewis, S. R. 2013, Simulating the Interannual Variability of Major Dust Storms on Mars Using Variable Lifting Thresholds, *Icar*, **223**, 344
- Newman, C. E., Lee, C., Mischna, M. A., Richardson, M. I., & Shirley, J. H. 2019, An Initial Assessment of the Impact of Postulated Orbit–Spin Coupling on Mars Dust Storm Variability in Fully Interactive Dust Simulations, *Icar*, **317**, 649
- Newman, C. E., & Richardson, M. I. 2015, The Impact of Surface Dust Source Exhaustion on the Martian Dust Cycle, Dust Storms and Interannual Variability, as Simulated by the MarsWRF General Circulation Model, *Icar*, **257**, 47
- Richardson, M. I., Toigo, A. D., & Newman, C. E. 2007, PlanetWRF: A General Purpose, Local to Global Numerical Model for Planetary Atmospheric and Climate Dynamics, *JGRE*, **112**, E09001
- Saidel, M., Wang, H., Battalio, J. M., Toigo, A. D., & Richardson, M. I. 2022, Mars Dust Storm Sequence Dataset (MDSSD), Harvard Dataverse, V6, doi:10.7910/DVN/0XB6KN
- Strausberg, M. J., Wang, H., Richardson, M. I., Ewald, S. P., & Toigo, A. D. 2005, Observations of the Initiation and Evolution of the 2001 Mars Global Dust Storm, *JGRE*, **110**, E02006
- Toigo, A. D., Lee, C., Newman, C. E., & Richardson, M. I. 2012, The Impact of Resolution on the Dynamics of the Martian Global Atmosphere: Varying Resolution Studies with the MarsWRF GCM, *Icar*, **221**, 276
- Toigo, A. D., & Waugh, D. W. 2022, Connections between the Transient Polar Warming and Solstitial Pause on Mars, *PSJ*, **3**, 208
- Torrence, C., & Compo, G. P. 1998, A Practical Guide to Wavelet Analysis, *BAMS*, **79**, 61
- Wang, H., & Gonzalez Abad, G. 2021, Cloud Masks Derived from Mars Daily Global Maps and an Application to the Tropical Cloud Belt on Mars, *Geosc*, **11**, 324
- Wang, H., & Richardson, M. I. 2015, The Origin, Evolution, and Trajectory of Large Dust Storms on Mars during Mars Years 24–30 (1999–2011), *Icar*, **251**, 112
- Wang, H., Richardson, M. I., Toigo, A. D., & Newman, C. E. 2024, Large Scale Oscillations in the Martian Tropical Cloud Belt, *JGRE*, **129**, e2024JE008479
- Wang, H., Saidel, M., Richardson, M. I., Toigo, A. D., & Battalio, J. M. 2023a, Martian Dust Storm Distribution and Annual Cycle from Mars Daily Global Map Observations, *Icar*, **394**, 115416
- Wang, H., Toigo, A. D., & Richardson, M. I. 2023b, Simulated Atmospheric Response to Large-Scale Dust Forcing and Implications for Martian Dust Storm Growth, *JGRE*, **128**, e2023JE007956
- Webster, P. J. 2020, Advancing Weather and Climate Science, Dynamics of the Tropical Atmosphere and Oceans (Wiley)
- Wheeler, M., & Kiladis, G. N. 1999, Convectively Coupled Equatorial Waves: Analysis of Clouds and Temperature in the Wavenumber-Frequency Domain, *JAtS*, **56**, 374
- Wilson, R. J., & Hamilton, K. 1996, Comprehensive Model Simulation of Thermal Tides in the Martian Atmosphere, *JAtS*, **53**, 1290
- Wolff, M. J., Clancy, R. T., Kahre, M. A., et al. 2019, Mapping Water Ice Clouds on Mars with MRO/MARCI, *Icar*, **332**, 24
- Wolff, M. J., Lopéz-Valverde, M., Madeleine, J.-B., et al. 2017, Radiative Process: Techniques and Applications, The Atmosphere and Climate of Mars, ed. R. M. Haberle et al. (Cambridge Univ. Press), 106
- Wolff, M. J., Smith, M. D., Clancy, R. T., et al. 2009, Wavelength Dependence of Dust Aerosol Single Scattering Albedo as Observed by the Compact Reconnaissance Imaging Spectrometer, *JGRE*, **114**, E00D04
- Yang, G.-Y., Hoskins, B., & Slingo, J. 2003, Convectively Coupled Equatorial Waves: A New Methodology for Identifying Wave Structures in Observational Data, *JAtS*, **60**, 1637