# Mars Atmosphere Simulations with ROCKE-3D: Nonlinear Dust Cycle Behavior Linked to Dust Radiative Effect

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# Introduction

- Goal of the study: To understand the importance of the dust radiative effect for the atmospheric dust cycle of Mars as a major factor in Mars' weather and climate.
- We carried out Mars atmosphere simulations, using the NASA Goddard Institute for Space Studies (GISS) Resolving Orbital and Climate Keys of Earth and Extraterrestrial Environments with Dynamics (ROCKE-3D) general circulation model (Way et al. 2017), with implemented interactive dust aerosol tracers.
- The simulated dust aerosol optical depth (AOD) is compared to observations (Montabone et al., 2015, 2020).
- Radiatively active dust and radiatively inactive dust experiments are compared with respect to the role of the dust radiative effect in the behavior of the dust cycle and linked variables.
- We are presenting some selected preliminary results here. Work in progress.

# Model

- Atmosphere component of ROCKE-3D, which is a generalized derivative for exoplanets of the NASA GISS Earth System Model (ESM) “ModelE” version 2.1+ (branch “tracersE3”), 5°x4° longitude by latitude resolution for Mars, 40 vertical layers (Way et al. 2017), coupled to the Suite of Community Radiative Transfer codes based on Edwards and Slingo (SOCRATES) (Edwards, 1996; Edwards and Slingo 1996), Mie theory for aerosols.
- The same sectional module for the atmospheric dust cycle as in the ESM, with four size bins for emission, transport, and deposition of dust tracer mass, ranging from 0.1-32 μm particle diameter (Miller et al., 2006).
- Probability density function scheme for dust emission to also account for subgrid scale variability of the wind speed from dry convection (dust devils), turbulent kinetic energy, and moist convection (latter not relevant for Mars).
- Advection is simulated using a quadratic upstream scheme (9 moments) to account for subgrid scale variation of tracer mass.
- Representation of gravitational deposition, dry turbulent deposition, and wet deposition of the dust tracers.
- The strength of the dust cycle can be scaled by a global factor of dust emission as a free parameter.

# Experiments

- A set of 16 experiments with radiatively active dust (depicted as Emis-A in figures), for different emission factors between 2.5 to 4.
- A set of 4 experiments with radiatively inactive dust (depicted as Emis-I in figures), for emission factors 2.5, 3, 3.5, and 4.
- Simulation lengths: 12 years each (Mars Years 24 to 35).
- Observations: Globally gridded dust aerosol optical depth (AOD) data for the Mars years 24 to 35 taken from literature, which are provided online[*] (Montabone et al. 2015, 2020). These observations data are based on retrievals using various instruments during different Mars missions (the Thermal Emission Spectrometer (TES) with Mars Global Surveyor, the Thermal Emission Imaging System (THEMIS) with Mars Odyssey, and the Mars Climate Sounder (MCS) with Mars Reconnaissance Orbiter (MRO).)

[*] url: http://www-mars.lmd.jussieu.fr/mars/dust_climatology/

# Results

See following slides. The slides with the figures can be found after the slides with the descriptions.

**Figure 1:** The model simulates an annual cycle of the dust AOD both for radiatively active dust and radiatively inactive dust, which resembles the annual cycle of the observed Mars dust AOD. However, the model simulates a single peak of the dust AOD around months 9/10, whereas the observations show a double peak with lower magnitude of the AOD. The model does not reproduce the "outliers" shown in the observations for individual years. These are global dust storms with high global dust AOD.

Notable differences between radiatively active and inactive dust simulations:

- The dust AOD increases strictly linearly with the emission factor in the inactive dust simulations.
- Inactive dust simulations tend to have higher dust AOD than radiatively active dust simulations for the same emission factor, especially in months with low dust AOD. That is, the radiative effect of dust tends to suppress dust emission (negative feedback).
- However, in some months with elevated dust emission, the dust AOD increases more for active dust than for inactive dust for higher emission factors. In some months, dust AOD in radiatively active dust simulations even exceeds the one from inactive dust simulations for the same higher dust emission factor (positive feedback). The interannual variability also increases for active dust. The contrast between the feedbacks suggests two possible regimes, depending on the strength of the dust radiative effect, with a bifurcation point between the regimes.
- Some radiatively active dust simulations show a hint of producing "outliers" with higher AOD in individual years.

**Figure 2 and Figure 3:** These Figures show the annual mean geographical distributions of the simulated dust aerosol optical depths for the different emission factors versus the retrieved AOD (Figure 2) and the differences between the simulated AOD and the observed ones (Figure 3). The locations of the major dust sources are well reproduced in the model.

However, for a mean simulated AOD that matches the observed one, the model overestimates the AOD near sources and underestimates it in remote locations. This can have multiple causes (like a mismatch between the dust size distribution in the model and the one in nature, or a transport problem). This bias is a common problem in global dust models also for Earth.

**Figure 4:** The comparison of the global mean emitted dust mass between active and inactive dust corroborates the findings in Figure 1.

**Figure 5:** The radiative effect of dust generally decreases the dust emission frequency. The stronger the radiative effect, the less frequent is dust emission in most months.

<u>Exception:</u> Months with elevated interannual variability. The dust emission frequency is positively correlated with the dust AOD.

**Figure 6:** The GCM mean surface wind speed is negatively correlated with the dust AOD in months with low dust AOD.

The correlation between the two variables becomes positive in months with high dust AOD.

**Figure 7:** The turbulent kinetic velocity scale represents the component of subgrid wind speed variability due to turbulence. The relationship between this variable and dust AOD is very similar to the one between mean wind speed and dust AOD.

**Figure 8:** The dry convective velocity scale represents the component of subgrid wind speed variability due to sensible heat flux fluctuations, which are also linked to dust devils. This component is inversely correlated with the strength of the dust radiative effect. The relative contribution of this component to dust emission is highest in months with low dust AOD.

**Figure 9:** This figure shows the warming effect of dust at the surface. The higher the dust AOD the higher is the warming effect.

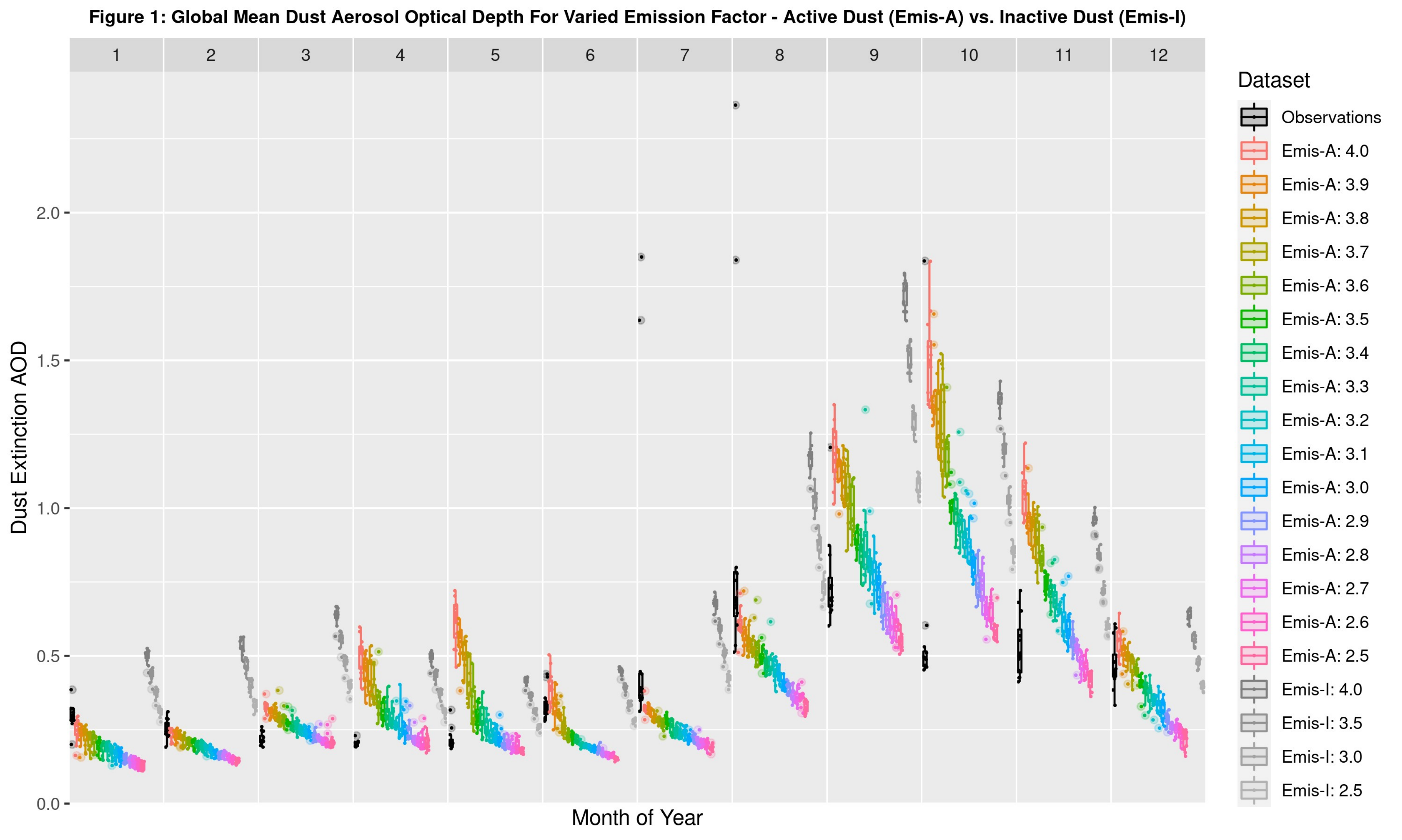


Figure 1: Global Mean Dust Aerosol Optical Depth For Varied Emission Factor - Active Dust (Emis-A) vs. Inactive Dust (Emis-I)
1
2
3
4
5
6
7
8
9
10
11
12
Dust Extinction AOD
0.0
0.5
1.0
1.5
2.0
Month of Year
Dataset
Observations
Emis-A: 4.0
Emis-A: 3.9
Emis-A: 3.8
Emis-A: 3.7
Emis-A: 3.6
Emis-A: 3.5
Emis-A: 3.4
Emis-A: 3.3
Emis-A: 3.2
Emis-A: 3.1
Emis-A: 3.0
Emis-A: 2.9
Emis-A: 2.8
Emis-A: 2.7
Emis-A: 2.6
Emis-A: 2.5
Emis-I: 4.0
Emis-I: 3.5
Emis-I: 3.0
Emis-I: 2.5

Figure 2: Dust AOD - Observations and Experiments - Annual Mean

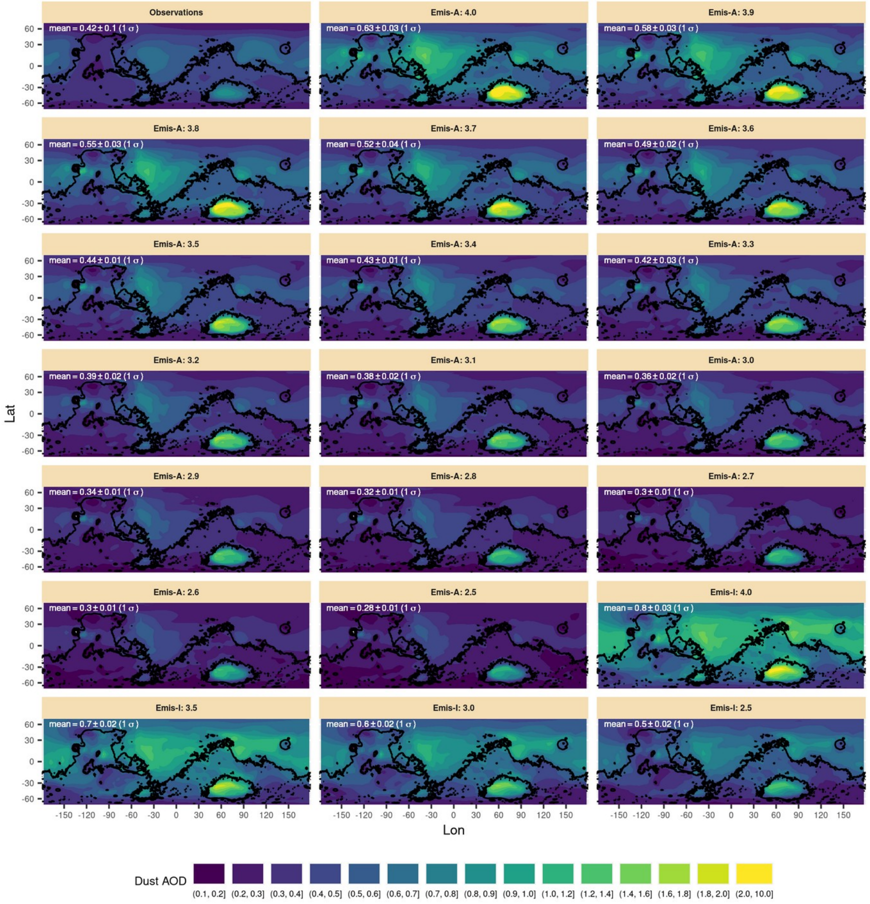



Figure 3: Dust AOD - Annual Mean Difference Between Experiments and Observations

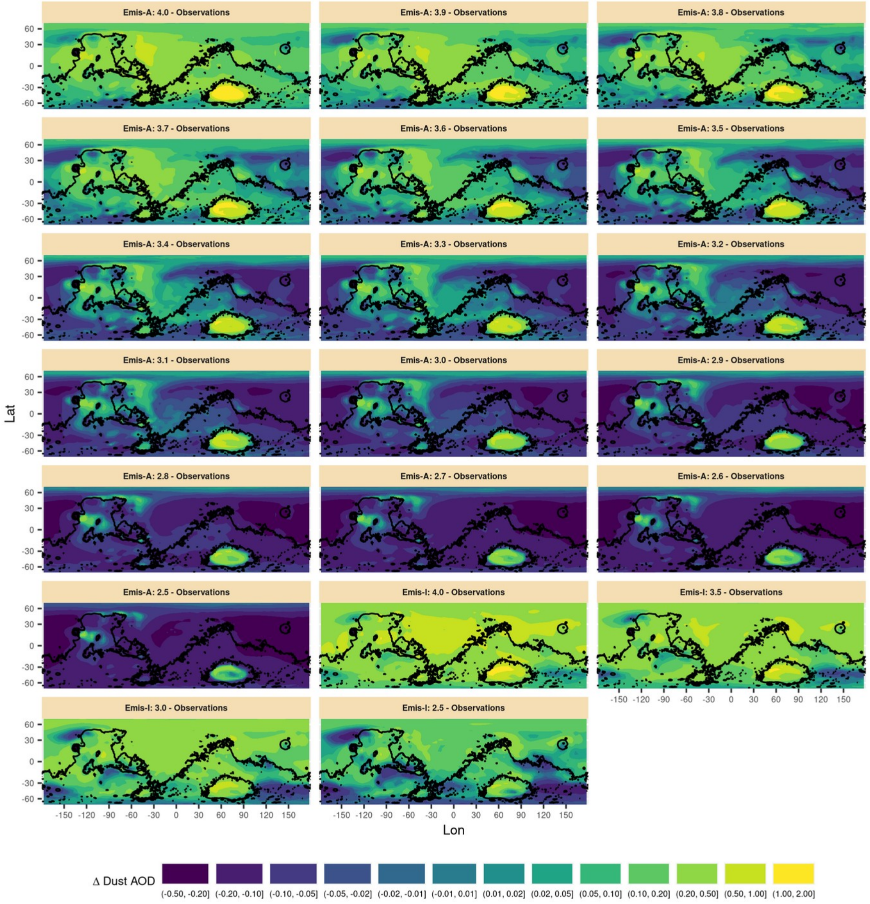
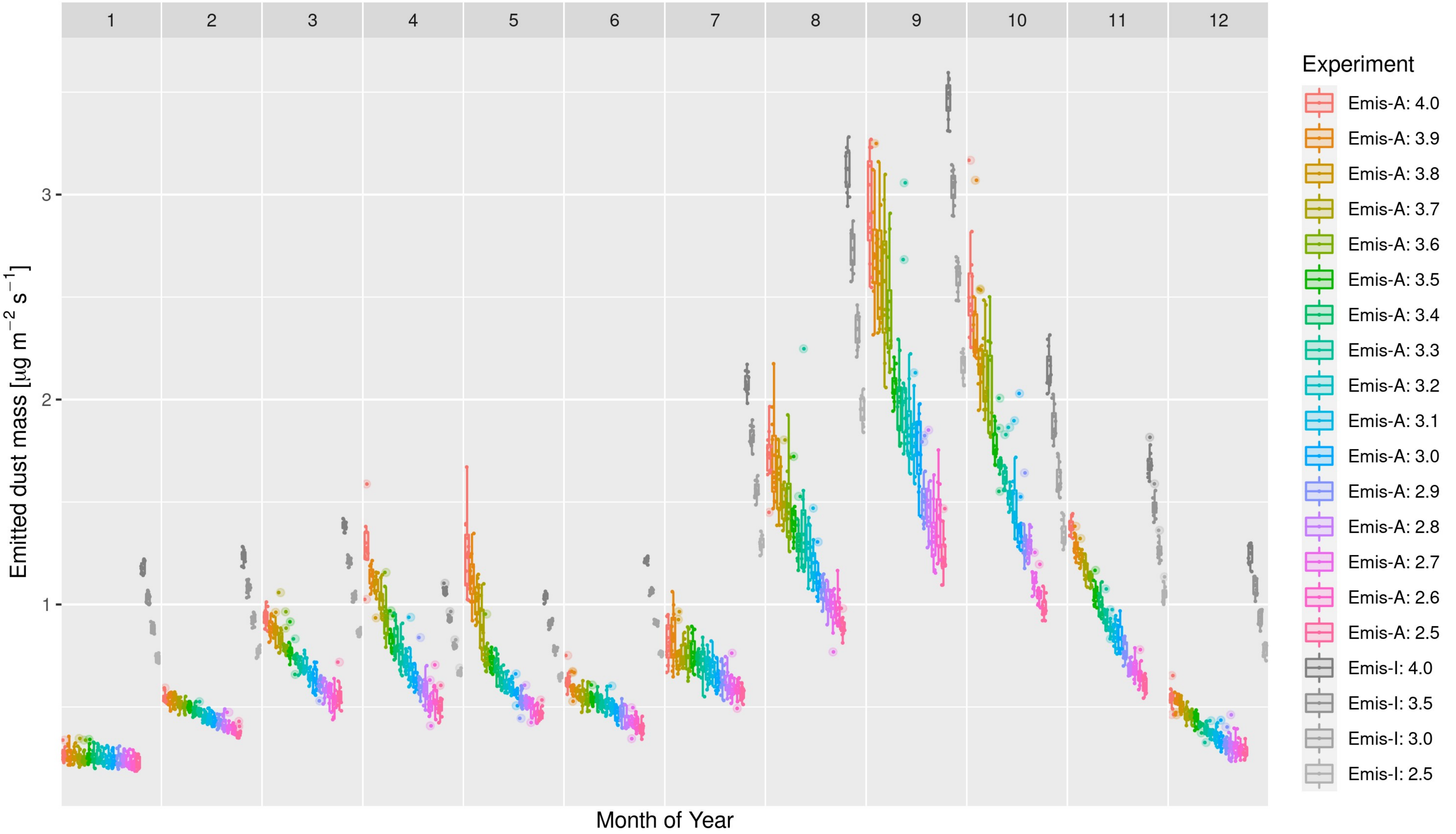


**Figure 4: Global Mean Emitted Dust Mass For Varied Emission Factor - Active Dust (Emis-A) vs. Inactive Dust (Emis-I)**



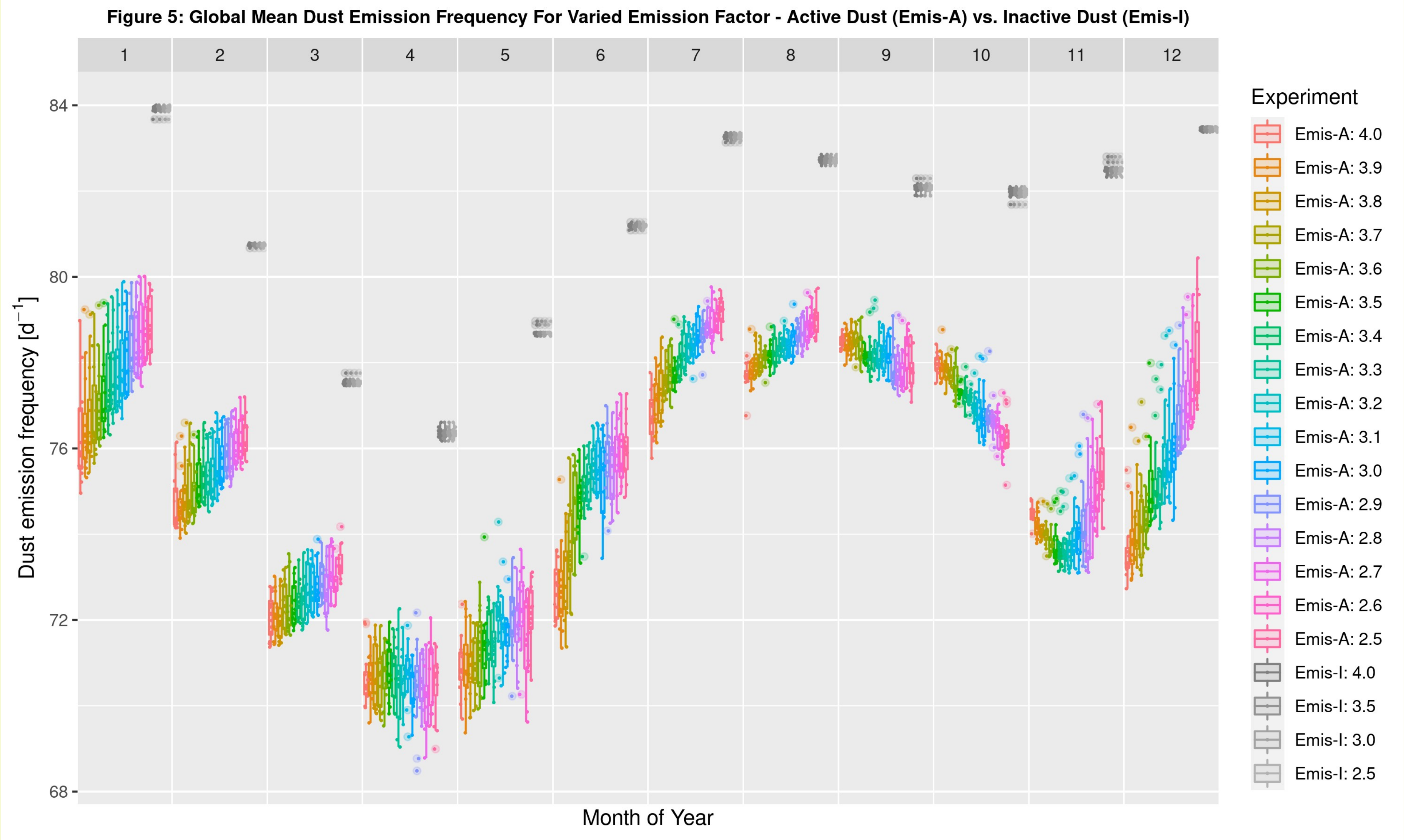


Figure 5: Global Mean Dust Emission Frequency For Varied Emission Factor - Active Dust (Emis-A) vs. Inactive Dust (Emis-I)
1
2
3
4
5
6
7
8
9
10
11
12
84
80
76
72
68
Dust emission frequency [d⁻¹]
Month of Year
Experiment
Emis-A: 4.0
Emis-A: 3.9
Emis-A: 3.8
Emis-A: 3.7
Emis-A: 3.6
Emis-A: 3.5
Emis-A: 3.4
Emis-A: 3.3
Emis-A: 3.2
Emis-A: 3.1
Emis-A: 3.0
Emis-A: 2.9
Emis-A: 2.8
Emis-A: 2.7
Emis-A: 2.6
Emis-A: 2.5
Emis-I: 4.0
Emis-I: 3.5
Emis-I: 3.0
Emis-I: 2.5

**Figure 6: Global Mean GCM Wind Speed For Varied Emission Factor - Active Dust (Emis-A) vs. Inactive Dust (Emis-I)**

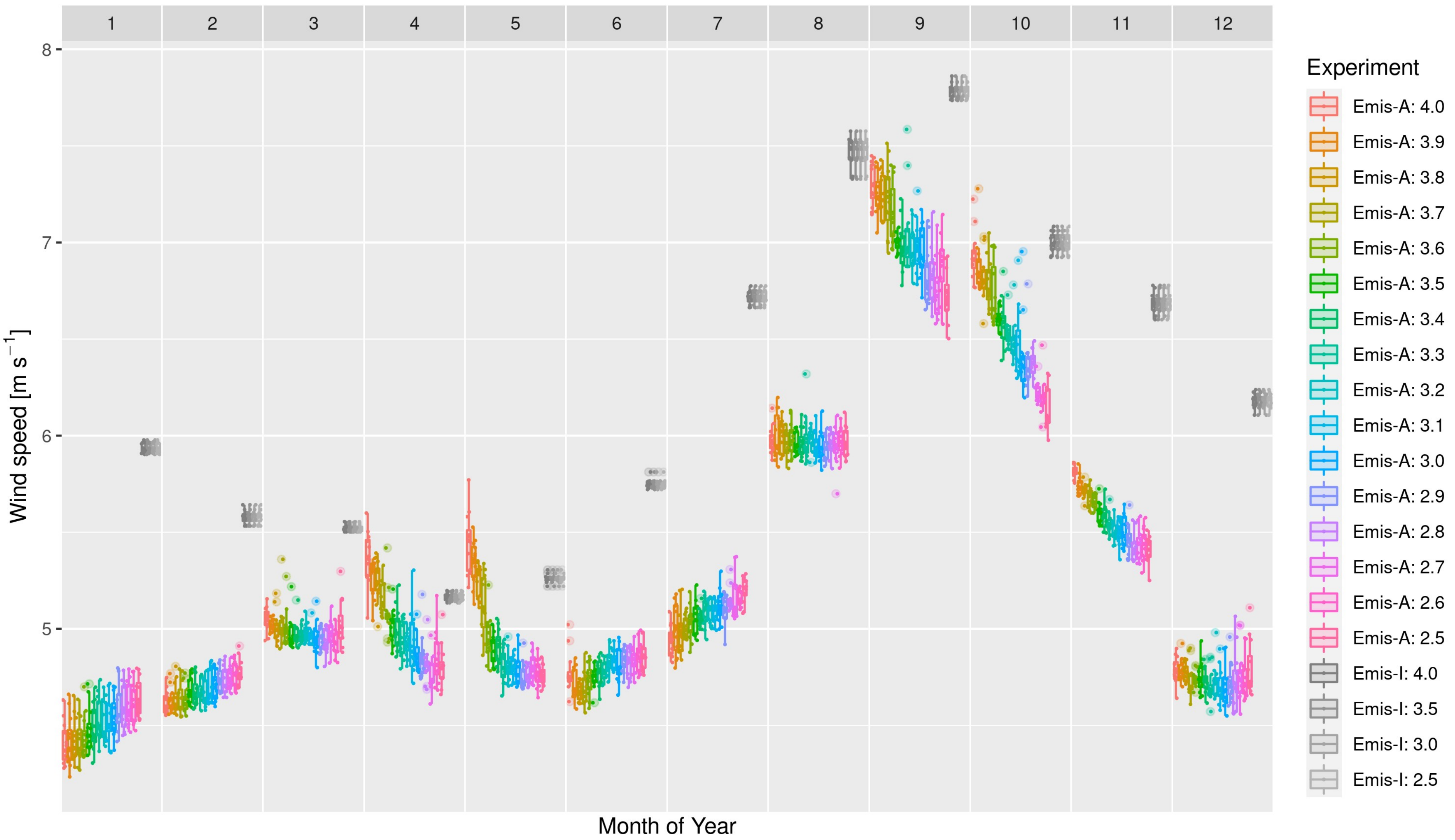
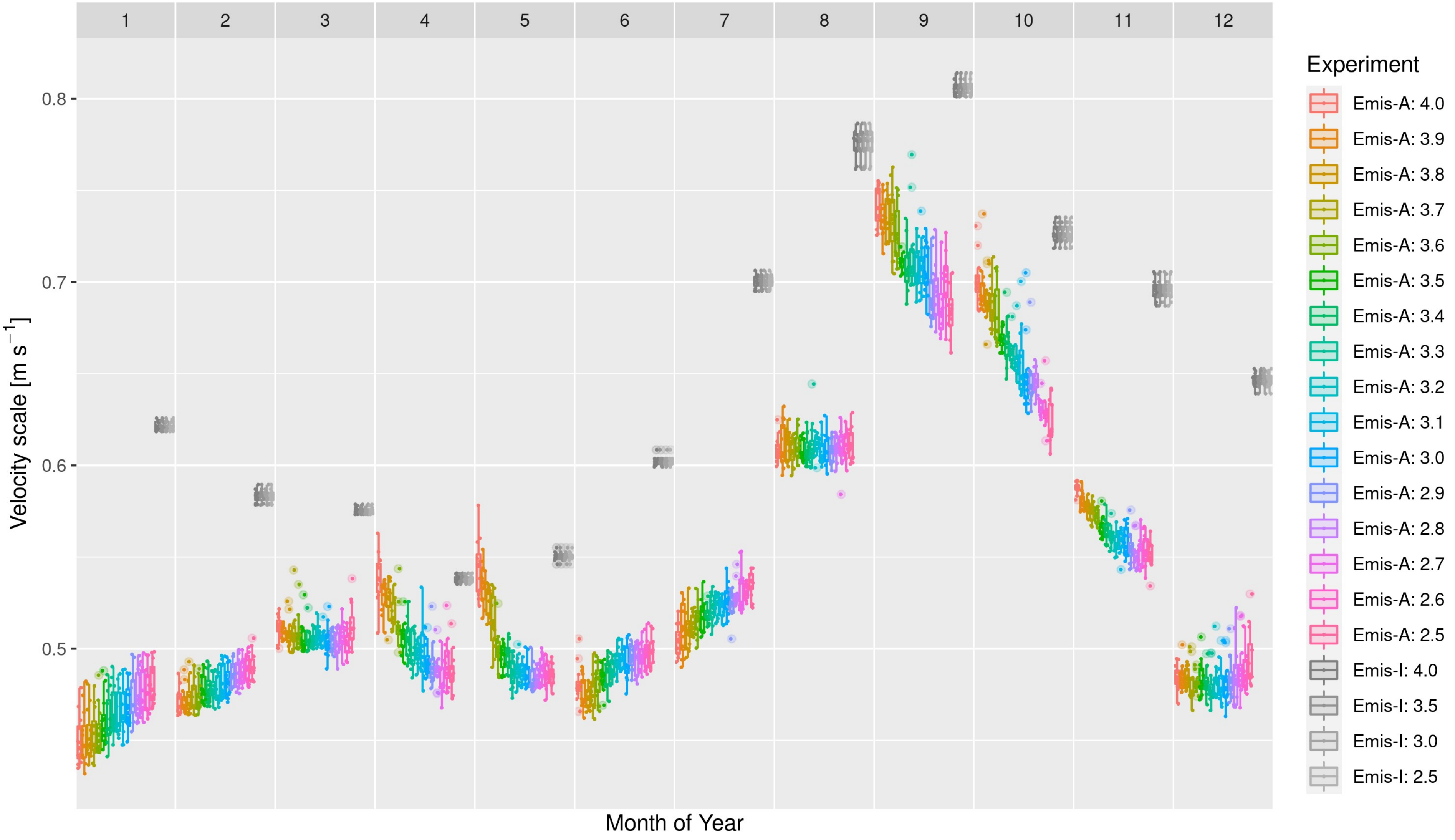


**Figure 7: Global Mean Turbulent Kinetic Energy Velocity Scale For Varied Emission Factor - Active Dust (Emis-A) vs. Inactive Dust (Emis-I)**



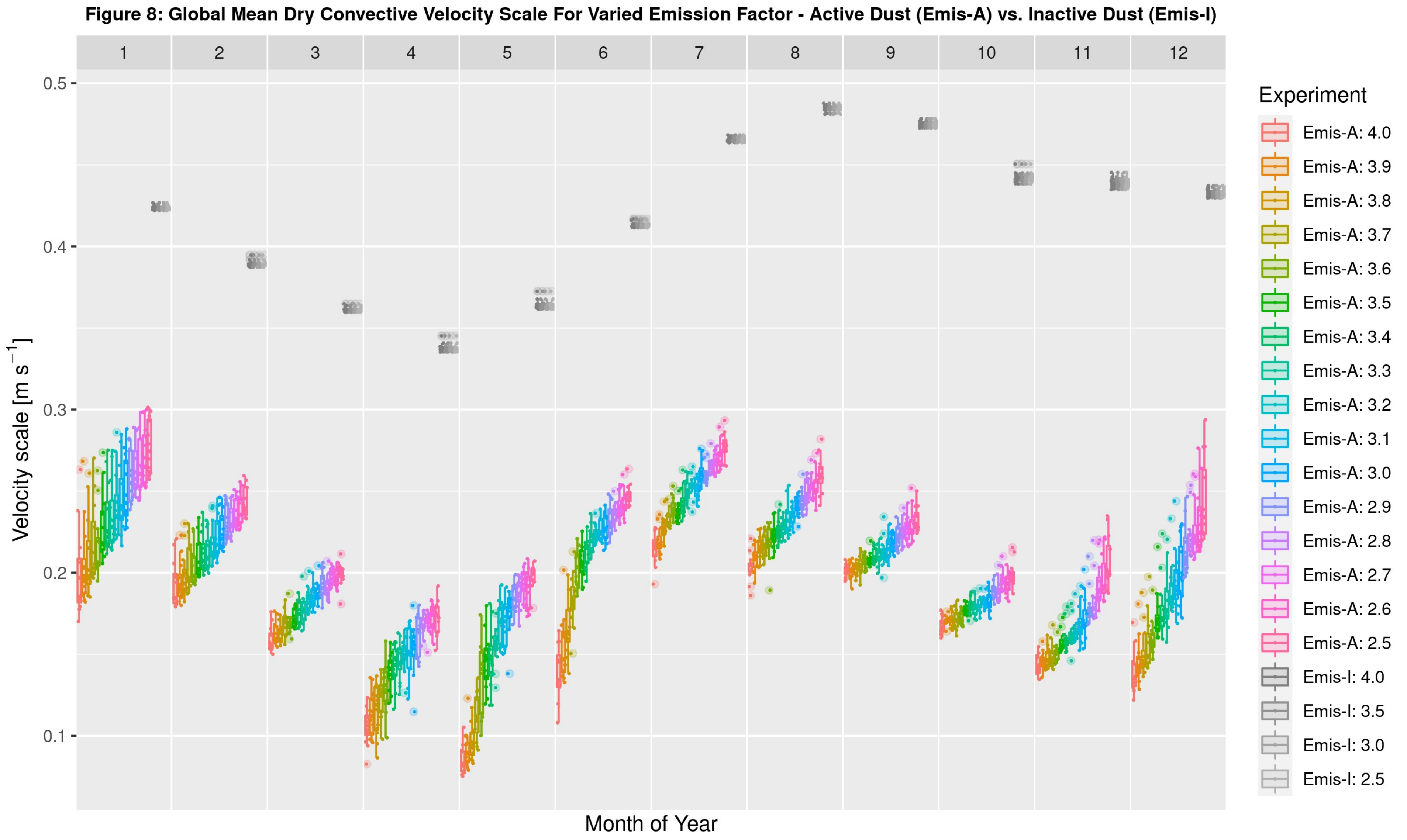
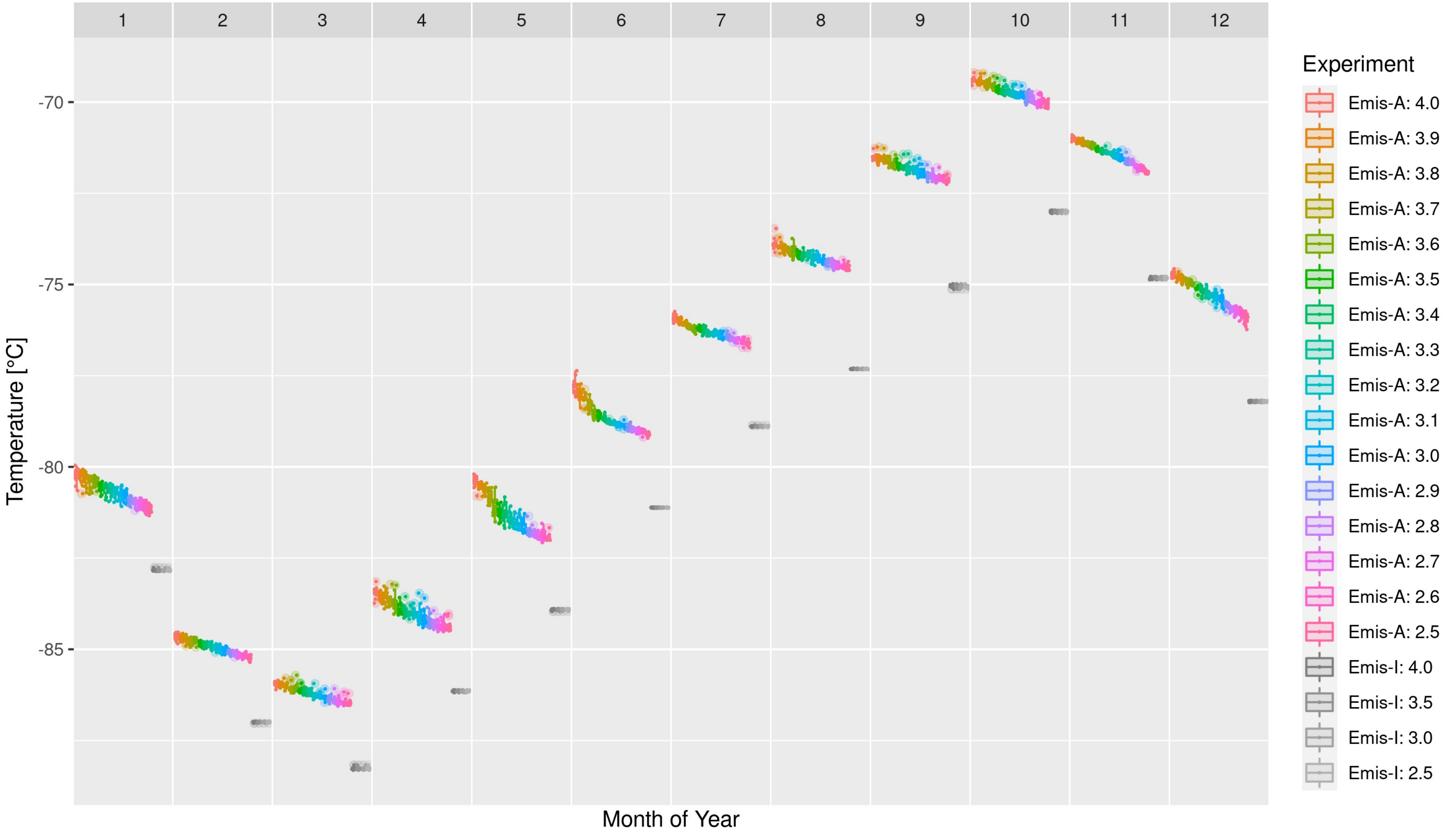


Figure 8: Global Mean Dry Convective Velocity Scale For Varied Emission Factor - Active Dust (Emis-A) vs. Inactive Dust (Emis-I)
1
2
3
4
5
6
7
8
9
10
11
12
0.5
0.4
0.3
0.2
0.1
Velocity scale [m s$^{-1}$]
Month of Year
Experiment
Emis-A: 4.0
Emis-A: 3.9
Emis-A: 3.8
Emis-A: 3.7
Emis-A: 3.6
Emis-A: 3.5
Emis-A: 3.4
Emis-A: 3.3
Emis-A: 3.2
Emis-A: 3.1
Emis-A: 3.0
Emis-A: 2.9
Emis-A: 2.8
Emis-A: 2.7
Emis-A: 2.6
Emis-A: 2.5
Emis-I: 4.0
Emis-I: 3.5
Emis-I: 3.0
Emis-I: 2.5

**Figure 9: Global Mean Surface Air Temperature For Varied Emission Factor - Active Dust (Emis-A) vs. Inactive Dust (Emis-I)**



# Summary and Conclusion

- ROCKE-3D with radiatively active dust aerosol tracers can qualitatively reproduce some features of the observed average annual cycle of Mars dust AOD, utilizing a dust module that originally was developed for application in an Earth system model. However, the simulations do not reproduce a double peak, only a single peak in the annual cycle of the dust AOD. We still cannot reproduce the “outliers” in the observations, events of dust storms occurring in some years, with very high aerosol optical depths, which engulf the whole planet Mars.

- For low dust conditions the radiative effect suppresses the dust cycle/AOD (negative feedback) In contrast, the dust AOD increases more for active dust than for inactive dust for higher emission factors in months of the annual cycle with elevated dust emission (positive feedback). The interannual variability also increases for active dust in these months.

- We hypothesize that the nonlinear behavior of the dust cycle, linked to a self-amplification of the dust cycle due to the radiative effect of dust, may be an essential aspect to understand the occurrence of global events with very high dust loads on Mars in some years.

# References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