The Present Day Atmospheric Dust Cycle and Dust Radiative Effect on Mars in NASA GISS ROCKE-3D.

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Introduction

Soil dust is among the most important factors contributing to the weather and climate variability of the Martian atmosphere. The Martian dust cycle encompasses all the processes that lift dust from surface reservoirs, transport it through the atmosphere, and deposit it back onto the surface, similar to the dust cycle on Earth [4].

Numerous Mars atmospheric models have been published in the scientific literature by now, and they are generally capable to replicate the broad structure of the Martian dust cycle with self-consistently generated wind-stress driven dust storms at scales ranging from local to global, background dust generating dust devils, the associated thermal structure of the atmosphere, and even aspects of the coupled dust and hydrological cycle. However, many clear deficiencies remain. In broad terms, dust cycle modeling is deficient with respect to the global sources and sinks of airborne dust and properly replicating the observed seasonality and interannual variability of Martian dust storms as well with respect to reproducing the planet encompassing dust storms with very high dust optical depths that occur ever some years.

Our work aims at better understanding the physics that underlies the Martian dust cycle by carrying out and analyzing decade-scale (in Mars years) simulations with a general circulation model (GCM) of the atmosphere. Here, we present results on the magnitude of the simulated climatological Martian dust cycle and its radiative effect as well as their structural uncertainty due to model assumptions, such as the the size distribution of emitted dust, the coupling of dust to the hydrological cycle, or constraints like the ground albedo.

Model

We use the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS) Resolving Orbital and Climate Keys of Earth and Extraterrestrial Environments with Dynamics (ROCKE-3D) atmospheric GCM [9, 8] at a resolution of $5^\circ \times 4^\circ$ longitude by latitude and 40 vertical layers. ROCKE-3D descends from NASA GISS Earth system model ModelE. It has been generalized to work for a wide range of exoplanet environments.

We incorporate the dust module that was developed for simulating the atmospheric dust cycle on Earth into the Mars version of ROCKE-3D, with some smaller modifications such as including an explicit dependency of the dust emission on the atmospheric density. The sectional module simulates dust emission from dry soils in five size bins covering a particle diameter range from 0.1 to $32\,\mu\mathrm{m}$. The dust emission scheme utilizes a probability function of dust emission that is based on subgrid-scale wind speed variability, which itself is parameterized as a function of other model variables. This variability depends on the sensible heat flux, which can be understood as an idealization of dust devils, the turbulent kinetic energy flux, and the downward mass flux in downdrafts caused by moist convection, although the contribution from latter is about Zero in the present-day Mars atmosphere. Dust emission is being initiated when the subgrid scale wind speed exceeds a wind speed threshold that itself technically depends on the content of moisture in the soil. Additional constraints on dust emission are derived from the Mars topography, adapting the concept of preferential dust sources [3] to Mars and the snow fraction covering the surface.

Dust transport is calculated with a quadratic upstream scheme that has been generally used for tracer advection in ModelE, increasing the effective resolution by including 2nd order moments in the advection calculations. Dust particles are removed from the atmosphere by gravitational settling, turbulent mixing in the surface layer, and wet removal processes. The current default Mars version of ROCKE-3D takes removal by collision with hydrometeors as wet removal process into account.

ROCKE-3D is coupled to the Suite of Community Radiative Transfer codes based on Edwards and Slingo [1, 2] to calculate the radiative transfer through the Mars atmosphere. This includes the calculation of scattering and absorption of radiation by dust particles both in the shortwave and longwave range, based on Mie theory. The model can be run in an interactive setting where the radiative forcing by atmospheric dust alters the state of the atmosphere and the surface fluxes. Those then feed back into the dust cycle. An alternative setting allows the model to be run without the dust radiative forcing having an effect on the atmospheric state and the surface fluxes.

Experiments

We present results from a series of experiments over 18 analyzed years (after two years spinup), which consist of a baseline simulation and additional experiments with modified assumptions. The strength of the dust cycle in the baseline simulation is calibrated by adjusting a global factor for dust emission so that the simulated climatological mean global mean total dust aerosol optical depth (DAOD) closely matches the climatological mean global mean DAOD from the gridded data provided by Montabone et al.[5, 6], which are derived from observations. Although the climatological global mean of the DAOD is calibrated in the baseline simulation, the simulated spatio-temporal distribution around it depends on the skill of the model to reproduce the essential features of the Martian dust cycle.

To assess uncertainty due to assumptions we present results from experiments with following modifications: variation in the dust emission parameter, variations in the assumptions on the ground albedo, variations in the efficiency of collision wet removal of dust particles, inclusion of a primitive parameterization of additional wet removal due to condensation with different efficiencies. We also did an additional experiment with an alternative size distribution for dust emission, which is based on the Aerosol Mineral Fraction approach[7].

All experiments with radiatively active dust have a partner simulation, in which the radiative effect of dust on the atmosphere and surface is switched off, everything else is equal. Since we carry out all radiative calculations as double calculation with and without the alteration of the radiative fluxes due to dust, this allows us to estimate both the instantaneous radiative forcing by dust and the dust radiative effect after the system has adjusted to the perturbation in the radiation fluxes.

Results

The calibrated dust AOD, matching the climatological global mean derived from the observations from Mars year 25 to Mars year 36, is approximately 0.43. With this value given, the climatological global dust emission and global dust load amount to $3,010 \pm 158\,\mathrm{Tg\,a^{-1}}$ (1 a = 1 Mars year) and $64 \pm 3\,\mathrm{Tg}$, respectively, in the baseline experiment, with the standard deviation is derived from the annual mean data. The model strongly underestimates the observed interannual variability in the DAOD, though.

In the partner experiment without coupling of the dust radiative effect to the atmospheric state and surface fluxes, the simulated dust emission and dust load amount to $7,299 \pm 205\,\mathrm{Tg\,a^{-1}}$ and $183 \pm 6\,\mathrm{Tg}$, respectively, and the DAOD is 1.17. That is, the factor of amplification in the DAOD between the radiatively active dust experiment and the radiatively inactive dust experiment is roughly 0.4, indicating a strong negative feedback between the dust radiative effect and dust emission.

The climatological mean instantaneous radiative forcing for the dust emission factor used in the baseline experiment is $-5.9\,\mathrm{W\,m^{-2}}$. The dust radiative effect after adjustment of the Mars climate to the radiative perturbation amounts to $-5.4\,\mathrm{W\,m^{-2}}$.

Variations in the physical assumptions lead to significant changes in the DAOD, dust emission/load, and radiative forcing. However, this sensitivity can be accounted for by scaling the global dust emission factor up or down in the model, since this is a free parameter in the model.

A notable exception are the experiments, for which the emitted mass size distribution of dust is varied, assuming a larger dust mass for large dust particle sizes due to aggregation of particles at the time of dust emission. Even though the DAOD closely matches the one from the observations, the emitted total emitted dust mass and dust load in the atmosphere are increased with a factor of about 3.6 and 1.3, respectively, for radiatively active dust. The instantaneous radiative forcing is reduced with a factor of about 0.4, whereas the dust radiative effect after adjustment of the simulated Mars climate to the radiative forcing by dust is reduced with a factor of 0.75.

Conclusions

This work presents results from simulations of present-day Mars climate with NASA GISS ROCKE-3D. The global mean dust aerosol optical depth on Mars is about an order of magnitude larger than the one observed on Earth. The simulated dust radiative effect is strongly negative on Mars, i.e, scattering of radiation back to space is the dominating effect, as this effect is only partially compensated by the warming effect of dust in the longwave range.

The estimates in our study come with the caveat that we also find substantial structural uncertainty due to model assumptions. The assumptions on the dust size distribution appear to be of particular significance due to the dependence of the ratio of scattering to the total extinction on the particle size.

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