UPDATE AND STATUS OF THE MARS CLIMATE MODELING CENTER AT NASA AMES RESEARCH CENTER

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Introduction: NASA Ames Research Center has a long-established history in the study and numerical modeling of Mars' atmosphere and climate. Such studies began with the late Jim Pollack and have continued under the leaderships of Bob Haberle, Jeff Hollingsworth, and now Melinda Kahre. Our group has grown to more than 10 members, including civil servants, research scientists, postdocs, and students. While we still prioritize science and the model development that supports it, we have recently enhanced efforts to make our codes and output publicly available and boost community engagement through the hosting of modeling tutorials, etc. Here our goal is to present the status of the Ames Mars GCM, our ongoing science projects, the tools we have recently made publicly available, and our plans for releases and continued community engagement.

Status of the New Ames Mars GCM: We are retiring our older, latitude-longitude dynamical core (our Legacy Mars GCM) and are completing the transition to the NOAA/GFDL cubed-sphere finite volume (FV3; Figure 1). This new dynamical core is highly parallelizable and scalable, which allows for higher resolution simulations and vastly improved throughput, has improved conservation properties, and does not have the "pole problem" that arises due to the singularities that are produced by the converging meridians at the poles in latitude/longitude grids. Additionally, this dynamical core has non-hydrostatic and nesting/stretching grid options.

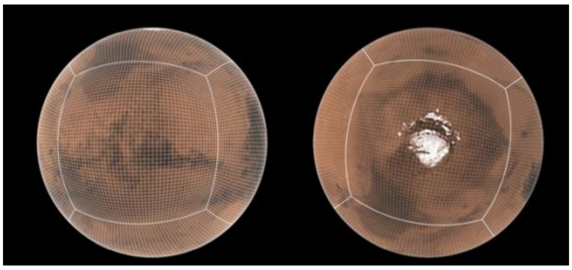

Figure 1: Cubed-sphere grid.

We have completed the porting of Ames-developed Mars physics routines [1] into the new GCM to complement the Mars physics routines that previously existed in the NOAA/GFDL FV3-based Mars GCM, and we have completed initial testing of this new capability by comparing the new GCM results to both the Legacy results and to available observations. We are now continuing model development efforts with the new GCM that are motivated by our science, mission support, and community engagement goals.

Physics Development: We continue to make progress developing physics routines to improve our simulation of the current and past Martian climates (Figures 2 and 3). Unless specifically referred to as the Legacy GCM, all future references to the GCM in this abstract are to the new Ames FV3-based GCM.

Improved Aerosol Treatment. The GCM currently has multiple options for including both the radiative effects of aerosols and the physical processes that govern their spatial and temporal distribution. We use both particle bins and moments to represent dust and water ice cloud particle size distributions.

Dust is critical to the Martian climate, so one area of continued development has been on improving the representation of dust in the model. Brownian and gravitational coagulation has been included [2] and a bi-modal distribution for dust has been implemented (*Urata et al., this meeting [3]*). These improvements have been used in investigations of global dust storms (see below). In the lower atmosphere, collisions between gas molecules and dust grains keep them thermally equilibrated at nearly the same temperature, but this equilibrium breaks down as low as 40 km above the surface and their temperatures diverge [4]. We have developed a 1-D radiative-convective model that includes the coupling physics of dust and gas, and we have implemented these modifications into the GCM (*Haberle et al., this meeting [5]*). The model conserves total dust energy while apportioning the available radiative energy streams into gas and dust heating.

Water ice clouds also critically influence the climate system, and we have improved the representation clouds and their radiative effects in the model. We have included the full, moment-based microphysics package that is described in [1] that includes water ice cloud nucleation growth and sedimentation with time splitting. In addition, we have the simple microphysics scheme [6, 7, 8], which allows for highly controlled cloud radiative effects.

Extended Vertical Domain. The GCM currently contains the physics packages needed to realistically simulate the atmosphere up to ~120 km, including Non-LTE near-IR heating and IR cooling, orographic and non-orographic gravity wave drag, and photochemistry. We are continuing to improve the representation of both orographic and non-orographic

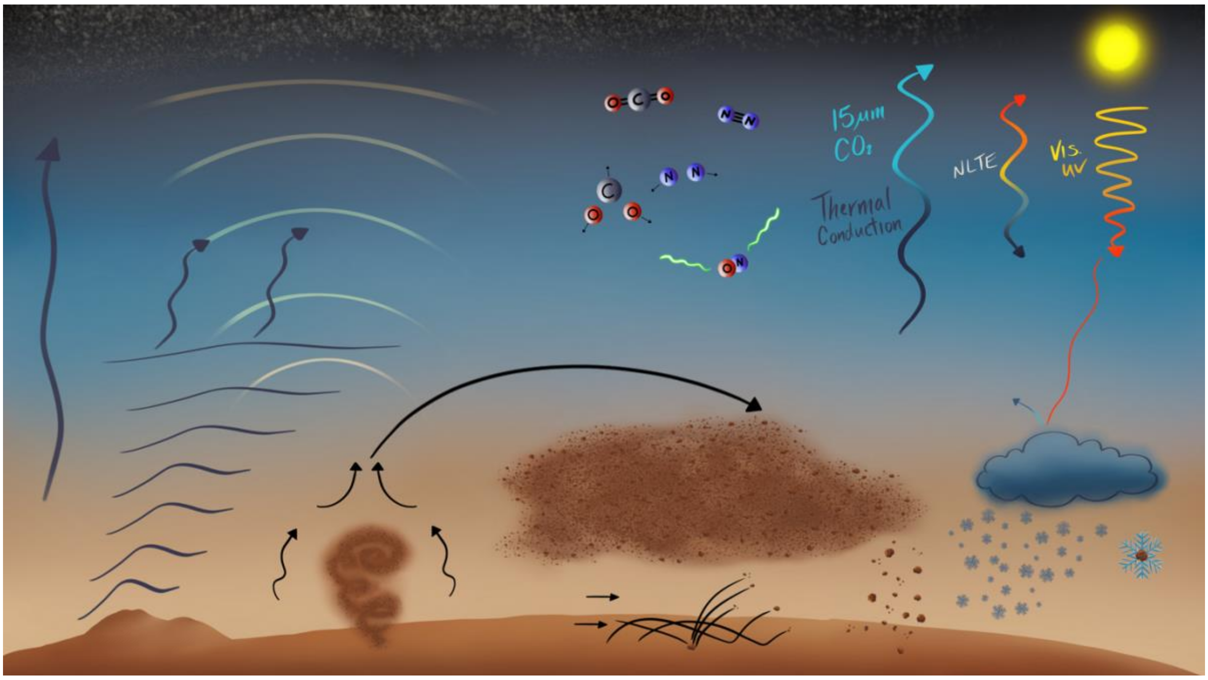

Figure 2: Current Mars processes diagram.

gravity wave forcing by comparing the effects of gravity waves in high horizontal (1/8°x1/8°) and vertical (~100 layers) resolution simulations to the effects produced by the parameterizations in the GCM. We are extending the model top up higher than ~120 km by including variable gravity and specific heat, and implementing and testing parameterizations for UV heating, thermal conduction, molecular viscosity, and molecular diffusion. We are switching from our current photochemistry scheme (from [9]) to the Kinetic Pre-Processor (KPP) scheme to be flexible for the science question being addressed (e.g., upper atmosphere, Exo-Mars, and Early Mars applications).

Early Mars Physics. Although the early Martian climate is challenging to simulate with GCMs, new capabilities of the FV3-based GCM will enable improved representations of the ancient hydrological cycle due to better polar region resolution with a cubed sphere grid and parallel architecture, which allows for longer runtimes. Our goal is to develop a comprehensive FV3-based GCM that can be used to understand the early Martian climate. We are porting the appropriate physics packages from the Legacy GCM to the FV3-based GCM, including an improved radiation code that includes the effects of collision-induced absorption (for CO_2, H_2, and CH_4), bulk H_2O and CO_2 cloud microphysics, and moist convection. Once we have thoroughly tested each package in the new GCM, we will focus on equilibrating the water cycle (including the locations of surface water ice) and testing the sensitivity of couplings between the CO_2, H_2O, and dust cycles.

Science Overview: We have many ongoing science projects related to current and past Mars, and Mars-like Exoplanets. We give an overview here, with a focus on projects that are presented at this meeting.

Climate Cycles. We are currently working on several projects that focus on the dust and water cycles on current-day Mars. We briefly describe these projects here.

Recent modeling efforts of the 2018 GDS highlight that climate models do not simultaneously capture the evolution of surface temperatures, semi-diurnal tide amplitude, and the decay rate of global column dust opacities, which suggests that significant changes in dust particle sizes may occur during the dust storm (e.g., [10, 11]). We show that using a self-consistent bimodal dust lifting scheme with a minor fraction of a small mode leads to an improvement in areas such as the diurnal surface temperature cycle and the semi-diurnal tide amplitude during the global dust storm (*Urata et al., this meeting [3]*).

The B regional dust storm is observed to occur at high southern latitudes near southern summer solstice. We model the B storm with the GCM at ~1°x1° horizontal resolution (*Batterson et al., this meeting [12]*). In our simulations, the B storm is made up of a series of dust plumes that are driven by strong radiative-dynamic feedbacks between airborne dust and incoming shortwave radiation.

Our ongoing water cycle investigations focus on the microphysical and radiative role of clouds on current day Mars. While in [1] we found that time-splitting the microphysical processes significantly reduced the cloudiness over the cap and yielded more realistic simulations of the water cycle, we continue to find that cloud formation over the NPRC is extremely sensitive to small changes in the environment. We are exploring the effects of high resolution on cloud formation over the NPRC and elsewhere, and we are utilizing our simple microphysics scheme in addition to our full

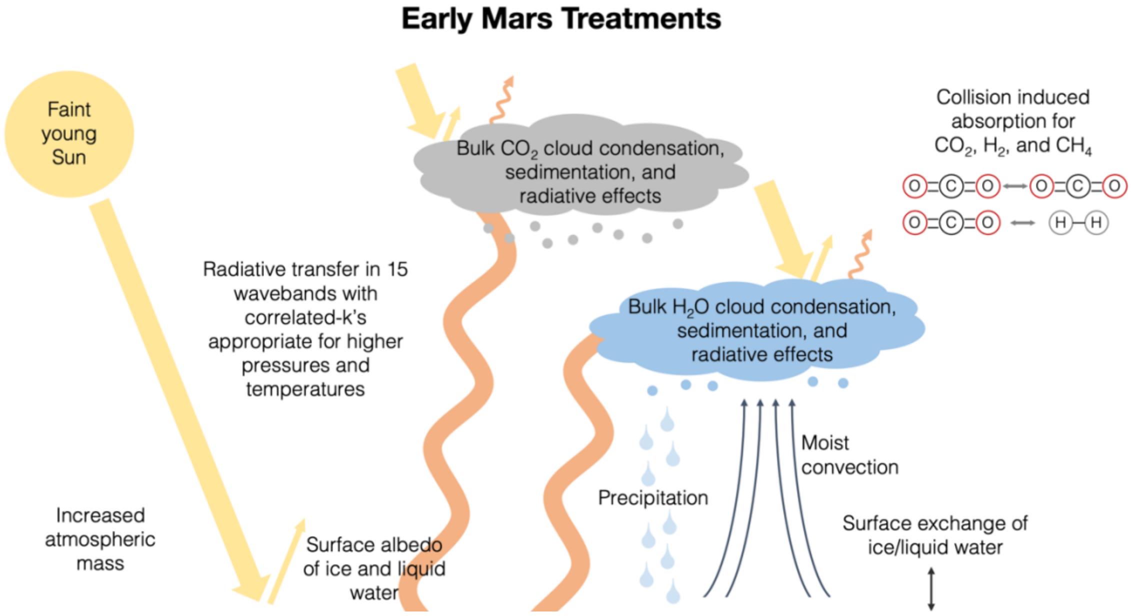

Figure 3: Early Mars processes diagram.

microphysics scheme to explore the radiative effects of clouds in the aphelion cloud belt and in the polar hoods.

Circulation and Dynamics. The evolving distribution of radiatively active dust and water ice clouds plays a major role in modulating the seasonal and interannual variation in the thermal forcing of the Martian atmosphere, and thus the resulting intensity of the circulation. Although we are interested in multiple aspects of these feedbacks, we focus here on tides.

The global tide includes westward propagating (sun-synchronous) waves driven in response to solar heating, as well as nonmigrating waves that result from zonal variations in the thermotidal forcing that are caused by variations in the surface and the distribution of aerosols. The migrating tides are of particular interest since they tend to be directly responsive to the aerosol distribution. There now exists an extended record of surface pressure observations at four locations in the Martian tropics, which can be used to put valuable constraints on the distribution and evolution of aerosols in the Martian atmosphere. We show that changes to the strength of the cloud radiative forcing yields better agreement to various tidal components as observed in the pressure records from the Martian surface (*Wilson et al., this meeting [13]*).

Middle and Upper Atmosphere Processes. The middle and upper atmosphere are influenced by the lower atmosphere and solar environment. This is being understood better with the observations from recent Mars missions. With the newly extended MGCM, we can now examine drivers that influence the lower atmosphere and upper atmosphere coupling in comparison to observations.

Polar warming and O_2 IR nightglow emissions are a product of the meridional circulation and are observed in similar latitude and altitude regions. However, their seasonal trends are observed to be different. We are examining the correlation between the polar warming and O_2 IR nightglow with respect to thermal and mechanical forcing mechanisms to achieve a deeper understanding of the meridional atmospheric transport (*Brecht et al., this meeting [14]*).

We are examining the behavior of the middle atmosphere nighttime thermal structure with respect to different lower atmosphere forcings. The recent discovery of the nightside warm layer [15] has launched curiosity of what could be driving this unexpected heating. We are utilizing our newly extended MGCM in conjunction with the most abundant temperature observations of the middle atmosphere (7 years of MAVEN/IUVS observations) to gain physical intuition on the nightside thermal structure variability (*Gkouvelis et al., this meeting [16]*).

One mechanism for energy and momentum transport through the whole atmosphere is gravity waves (GW). We use gravity-wave resolving GCM simulations at high horizontal (1/8°x1/8°) resolution with ~100 vertical layers and simulations at low horizontal (~4°) resolution with the orographic gravity wave drag parameterization from [17] in the new FV3-based GCM. The objective is to use the resolved wave-mean flow forcings at high resolution to refine the characteristics for the GWs implemented in the subgrid-scale parameterization (at lower resolution). The end goal is to better represent the unresolved dynamical effects of the GWs on the atmosphere in the new FV3-based GCM (*Kling et al., this meeting [18]*).

Early Mars. The early Martian climate has been the subject of scientific debate for decades. A range of observed fluvial features [19, 20, 21] imply warm and wet conditions occurred at least intermittently ~3.5-4 Gya but reproducing these conditions with climate models is difficult [22]. We aim to improve our understanding of early Mars climate conditions and active processes during the Noachian. We are currently investigating the role of CO_2 clouds on early Mars and how they affect the thermal structure of the atmosphere through condensation and through their radiative effects as they scatter in both the visible and the infrared (*Steakley et al., this meeting [23]*). Additionally, we are exploring reducing greenhouse environments with the GCM that result from impact degassing [24]. We find that large impactors (>100 km in diameter) that produce H_2 in 2 bar CO_2 atmospheres can induce long lived above-freezing surface conditions (*Steakley et al., submitted [25]*). Individual impacts could induce 10s-100s of m of surface degradation over 10^5 years, which would account for a fair portion of the total Noachian crater degradation estimated by [26] (~200-1000 m).

Mars-like Exoplanets. Arid land planets like Mars may be common in planetary systems outside of our Solar System. It is important to understand their climate, potential habitability and defining characteristics to aid in their detection and characterization. Our results show that dust radiative heating, particularly in the high atmosphere, fundamentally modifies the climate of a dry planet at Earth insolation (*Hartwick et al, this meeting [27]*). When dust is lofted into the middle atmosphere, heating rapidly strengthens the zonal mean circulation and amplifies the diurnal and higher harmonic components of the thermal tide, which together positively feeds back on the process of dust lifting. The atmosphere becomes very dusty and strong greenhouse warming of the surface is predicted to occur. We plan to continue investigating this topic with interactive and coupled dust and water cycles to study how cloud formation and the radiative effects of clouds affects the dust cycle and climate. We also plan to simulate land planet climates around M-stars, the most likely targets for future observation and characterization of terrestrial exoplanets.

Public Releases and Community Tutorial: We have focused recently on publicly releasing GCM source code, GCM output, and an analysis software package for processing model output. These efforts are summarized in the following paragraphs.

Legacy Mars GCM Source Code and Output. We have released source code and output from the Legacy GCM. The source code is available on the NASA GitHub (https://github.com/nasa/legacy-mars-global-climate-model), and output from the simulations described in [1] are available on the NAS Data Portal (https://data.nas.nasa.gov/mcmc/data_legacygcm.php).

Community Analysis Pipeline (CAP). Analyzing and visualizing complex multi-dimensional GCM output is challenging. We are therefore developing an analysis software pipeline for community and internal use that is accessible, comprehensive, and versatile. We are using Python for its open-source and cross-platform utility and the self-descriptive netCDF data standard. We have developed an initial version of the analysis pipeline that provides a streamlined workflow for users to access, analyze, and visualize the Legacy and FV3-based GCM output. It is available on GitHub (https://github.com/alex-kling/amesgcm). We are adding advanced diagnostics and interfaces to observational data sets and other publicly available models/types of output (e.g., Mars Climate Database, OpenMars, EMARS) for comparison with our GCMs.

Legacy GCM and CAP Tutorial. We hosted a virtual modeling tutorial in the Fall of 2021 with the goal of teaching new users how to use and analyze output from the Legacy Mars GCM. The tutorial included lectures and hands-on sessions to teach participants about the basic physics in the model, its subroutines and flow diagrams, how to make changes to the code, how to compile and run the model, and how to analyze model output. Students, teachers, and researchers with a range of numerical modeling experiences participated. Tutorial materials are available at: https://www.nasa.gov/mars-climate-modeling-center-ames/MarsGlobalClimateModelTutorial.

New Ames Mars GCM Code and Output Release. We plan to release the new FV3-based Ames Mars GCM in the Fall of 2022. This will include both a source code release on GitHub and a model output release on the NAS Data Portal. Our plan going forward is to release a new version of the code and output yearly. The initial release will include basic current Mars physics only (CO_2 and dust cycles; model top at ~90 km), but future releases will include increased capabilities.

Conclusions: In addition to continuing to make progress on our science and model development goals, we are committed to becoming as valuable of a community resource as possible. This will involve future model and tool releases, tutorials, and workshops. We are open to suggestions, so please feel free to get in touch.

References: [1] Haberle et al. (2019), Icarus, 333; [2] Bertrand et al. (2021), EPSC Meeting; [3] Urata et al. (2022), 7th MAMO; [4] Goldensen et al. (2008), GRL, 35(8); [5] Haberle et al., (2022), 7th MAMO; [6] Montmessin et al. (2004), JGR, 109(E10); [7] Hinson and Wilson (2004), JGR, 109(E1); [8] Wilson and Guzewich (2014), GRL, 31(10); [9] Levèfre et al. (2004), JGR, 109(E7); [10] Bertrand et al. (2020), 125(7); [11] Montabone et al. (2020), JGR, 125(8); [12] Batterson et al., (2022), 7th MAMO; [13] Wilson et al., (2022), 7th MAMO; [14] Brecht et al., (2022), 7th MAMO; [15] Nakagawa et al. (2020), JGR, 125(9); [16] Gkouvelis et al., (2022), 7th MAMO; [17] Palmer et al. (1986), QJRMS 112(474); [18] Kling et al., (2022), 7th MAMO; [19] Craddock and Howard (2002) JGRwilson a, 107; [20] Kite (2019) SSR, 215(1); [21] Kite and Daswani (2019) EPSL, 524; [22] Wordsworth (2016) AREPS, 44; [23] Steakley et al., (2022), 7th MAMO;

[24] Haberle et al. (2019) GRL, 46(22); [25] Steakley et al. (2022), Icarus, *submitted*; [26] Golombek et al. (2006), JGR, 111(E12); [27] Hartwick et al., (2022), 7th MAMO.