

THE MARS CLIMATE MODELING CENTER AT NASA AMES RESEARCH CENTER: OVERVIEW OF RECENT SCIENCE, MODEL DEVELOPMENT, AND PROGRESS MAKING TOOLS PUBLICLY AVAILABLE AND ACCESSIBLE. M. A. Kahre¹, R. J. Wilson¹, R. A. Urata², A. S. Brecht¹, K. E. Steakley¹, C. M. Batterson², V. Hartwick², A. Kling², C. E. Harman¹, and M. Mester³. ¹NASA Ames Research Center, Moffett Field, CA, USA, ²Bay Area Environmental Research Center, Moffett Field, CA, USA, ³NASA Postdoctoral Program, NASA Ames Research Center, Moffett Field, CA, USA.

Introduction: In addition to conducting science investigations on the atmosphere and climate of Mars, a main function of the Mars Climate Modeling Center at NASA Ames research center is to develop, maintain, and make available to the community state-of-the-art Mars Global Climate Models (MGCMs). Our goal here is to present the status of the Ames MGCM, an overview of our ongoing science projects, the tools we have recently made publicly available, and our plans for releases and continued community engagement.

Status of the Ames Mars GCM: We have completed the transition from the latitude-longitude dynamical core (the Legacy MGCM) to the NOAA/GFDL cubed-sphere finite volume (the FV3-based MGCM). This 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. We are now continuing model development efforts with the FV3-based MGCM that are motivated by our science and community engagement goals.

Improved Aerosol Treatment. The MGCM currently has multiple options for including both the radiative effects of aerosols and the physical processes that govern their spatial and temporal distribution. Dust is critical to the Martian climate, so one area of continued development has been improving the representation of dust in the model by implementing a bi-modal distribution for dust. Water ice clouds are also critically important, and we have included the full, moment-based microphysics package described in [1].

Extended Vertical Domain. The MGCM 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 extending the model above ~120 km by implementing and testing parameterizations for UV heating and thermal conduction. We are switching from our current photochemistry scheme (from [2]) to the Kinetic Pre-Processor (KPP) scheme to allow for increased flexibility when using diverse modeling configurations (e.g., for upper atmosphere, Exo-Mars, and Early Mars applications).

Early Mars Physics. The MGCM has the capability to run with physics treatments appropriate for the early Martian climate. This includes running with a more massive CO₂ atmosphere, reduced solar flux to represent the faint young Sun, and a radiation code appropriate for massive atmospheres that can also account for collision-induced absorption (for CO₂, H₂, and CH₄). We are porting early Mars cloud physics packages from the Legacy GCM to the FV3-based GCM, including, bulk H₂O and CO₂ cloud microphysics, and moist convection. The 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. In future work, we will test the sensitivity of couplings between the CO₂, H₂O, 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. 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., [3, 4]). 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 [5]*). 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 global cloud formation is sensitive to small changes to microphysical parameters (*Kahre et al., this meeting [6]*).

Atmospheric Dynamics. We have multiple ongoing projects that focus on atmospheric dynamics and on how radiative-dynamic feedbacks affect the circulation and aerosol fields. First, we show that the evolving response of key modes of the global-scale thermal tide

to seasonal and episodic changes in the strength of dust and ice cloud radiative forcing are clearly reflected in the diurnal variations in surface pressure present in the extended record of observations at four lander locations in the tropics (*Wilson et al., this meeting [7]*). Second, we are investigating the influence of topography on the strength of transient eddies in the southern hemisphere (*Mester et al., this meeting [8]*). Third, we have compared a series of simulations progressing from low to high spatial resolution to show that gravity waves (resolved at high-resolution and parameterized at lower resolutions) significantly impact the momentum balance of the atmosphere in the tropics and subtropics, particularly during the solstice seasons (*Kling et al., this meeting [9]*). Finally (and relatedly), we are studying the response of planetary-scale waves and gravity waves to the regions of high inertial instability that most prominently develop in the tropics during the solstice seasons (*Wilson et al., this meeting [10]*).

Middle and Upper Atmosphere Processes. The middle and upper atmosphere are influenced by the lower atmosphere and solar environment, which is becoming more evident from observations from recent Mars missions. With the newly extended MGCM, we can now examine drivers that influence the coupling between the lower and upper atmosphere in comparison to observations. We are examining the behavior of the mesopause with respect to different lower atmosphere forcings (*Brecht et al., this meeting [11]*).

Early Mars. The early Martian climate has been the subject of scientific debate for decades. A range of observed fluvial features [12, 13, 14] imply warm and wet conditions occurred at least intermittently ~3.5-4 Ga but reproducing these conditions with climate models is difficult [15]. We aim to improve our understanding of early Mars climate conditions and active processes during the Noachian. We are currently investigating sensitivities of the early Mars hydrological cycle to key parameters including obliquity, atmospheric mass, pre-Tharsis topography, and surface water reservoirs (*Steakley et al., this meeting [16]*).

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. Results from the exoplanet configuration of the NASA Ames FV3-based Mars GCM show that dust cycle is a significant driver of climate state for Mars-like exoplanets in the habitable zone of G and M stars. Notably, dust can stabilize tenuous CO₂ atmospheres against collapse for tidally locked planets, suggesting that dust may play a crucial role in maintaining habitability in M star systems that are a primary focus of JWST and future space telescope observations (*Hartwick et al., this meeting [17]*).

Analysis Tools, Public Releases, and Tutorials:

Community Analysis Pipeline (CAP). Analyzing and visualizing complex multi-dimensional GCM output is challenging. We have developed (and are continuously adding new functionalities to) an analysis software pipeline for community and internal use that is accessible, comprehensive, and versatile. We use Python for its open-source and cross-platform utility and the self-descriptive netCDF data standard. CAP is available on GitHub (<https://github.com/NASA-Planetary-Science/AmesCAP>). 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, MarsWRF, EMARS) for comparison with our GCMs (*Batterson et al., this meeting [17]*).

GCM Source Code and Output. We have released source code and output from the FV3-based MGCM. The source code is available on the NASA GitHub (<https://github.com/nasa/AmesGCM>), and output from a reference simulation is available on the NAS Data Portal (<https://data.nas.nasa.gov/mcmcref/fv3betaout1/>). Finally, we have developed a web interface for easier access to model output that we will launch soon.

GCM and CAP Tutorial. We hosted a virtual modeling tutorial in the Fall of 2023 with the goal of teaching users how to use and analyze output from the FV3-based MGCM. The tutorial included lectures and hands-on sessions to teach participants about the basic physics in the model, how to compile and run the model, and how to analyze model output using CAP. Students, teachers, and researchers with a range of numerical modeling experiences participated.

Conclusions: In addition to making progress on our science and model development goals, we are committed to being a valuable community resource.

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