PERSPECTIVES ON MARS ATMOSPHERE DATA ASSIMILATION. Steven J. Greybush[1], Luca Montabone[2,3,4], Roland M. B. Young[5], and the MADA2018 Team*, [1]Department of Meteorology and Atmospheric Science, The Pennsylvania State University, University Park, PA, USA. (sjg213@psu.edu), [2]Space Science Institute, Boulder, CO, USA. [3]Centre for Mars Meteorology Monitoring, Paneureka, Le Bourget-du-Lac, France. [4]Laboratoire de Météorologie Dynamique / Institut Pierre-Simon Laplace (LMD/IPSL), Sorbonne Université, Centre National de la Recherche Scientifique (CNRS), École Polytechnique, École Normale Supérieure (ENS), Paris, France. [5]Department of Physics, SUPA, University of Aberdeen, King's College, Aberdeen, UK.

Introduction: Data assimilation (DA) is the analytical process of combining available observations and a numerical model to produce the best estimate of the state of a system. Atmospheric data assimilation has been widely used in terrestrial weather forecasting and climate studies for at least the last 60 years. Since the early 2000s, it has been applied with success to the atmosphere of Mars, and even more recently to that of Venus. After more than a Martian decade of continuous atmospheric observations, the need to discuss the current and future directions of Mars atmospheric data assimilation (MADA) emerged. To this purpose, a first workshop was organized to connect those researchers working on the modeling techniques with those providing the data, also benefiting from the contribution of researches with specific experience in Earth and Venus data assimilation. This workshop (MADA 2018) was held in the French city of Le Bourget-du-Lac on August 29–31, 2018. Twenty-nine scientists from institutions based in the USA, France, the UK, Japan, the UAE, Italy, and Belgium attended it. For three days, the participants discussed together what lessons they have learned so far, what challenges remain, and what opportunities lie ahead for atmospheric data assimilation on Mars. MADA 2024, a follow-up to that workshop, is planned for just after the 10th Mars Conference in Pasadena, CA on July 26, 2024.

Data assimilation can interpolate between observations in space, convey information to variables not observed, and transmit information forward in time with a dynamical model. In addition to providing initial conditions for atmospheric models and constraining chaotic flow (such as traveling waves), it can also help when models are missing key physical processes, or model parameters need to be tuned. Using data assimilation for an extended observation dataset produces a reanalysis, which is a reconstruction of the historical atmospheric state using a constant modeling and assimilation system.

Achievements in Mars Data Assimilation: Data assimilation for Mars is a young field, with the first published works appearing in the 1990s, and the first reanalyses appearing early in the 21st century. MACDA, the first extended duration Mars reanalysis, is based on the analysis correction scheme and assimilates MY24-27 MGS-TES observations of temperature and integrated column dust opacity [1]. A key aspect of ensemble-based methods is the ability to estimate flow-dependent error covariances from an ensemble, and therefore represent uncertainty in assimilated states. EMARS is based on the LETKF ensemble-based scheme and assimilates MGS-TES during MY24-26 and MRO Mars Climate Sounder (MCS) temperature profiles from MY29-31. [2] MACDA II extends to the MCS era with vertically resolved dust profiles [3]. OpenMars [4] spans both the MGS and MRO eras and includes TES water cycle and ozone observations from SPICAM with the analysis correction scheme. Finally, the broader spatial coverage of temperature observations provided by EMIRS has been assimilated in [5], and TGO data in [6] using ensemble-based approaches. A number of other studies have explored optimal assimilation strategies with real and simulated observations for Mars, as well as applied assimilation products to study various aspects of the Martian atmosphere and dynamics.

Observational Requirements for Data Assimilation for Future Missions: The foundation for successful data assimilation is an observing system with satisfactory coverage to provide adequate constraints on the state of the atmosphere. With the aid of the dynamical and physical processes inherent in a Mars Global Climate Model, the assimilation algorithm can reconstruct the state of the Martian atmosphere at regular spatial and temporal intervals. However, various atmospheric phenomena may have different requirements with respect to the measurement type and spatial and temporal resolution. Therefore, as a group the MADA2018 workshop attendees arrived at a consensus for qualitative requirements and priorities for observations to constrain various physical phenomena. The group focused on processes in the atmosphere below ~100 km altitude, as data assimilation has not yet been applied to the upper atmosphere of Mars. The table discusses which measurements are required or desired, and whether spatial/temporal or column/profile priority are favored, to analyze various phenomena in the Martain atmosphere. These phenomena include the zonal mean circulation, seasonal dust cycle, transient eddies, dust storms, thermal tides, water cycle, active and passive species, surface interactions, gravity waves, and the CO_2 cycle.

Observing System Simulation Experiments for Future Missions: Observing System Simulation Experiments (OSSEs) provide the capability to assess the ability of data assimilation systems to constrain the state of the atmosphere using present or hypothetical future observations. The premise of an OSSE is that observations are sampled from a known "truth", or nature run. This nature run is a freely running Global Climate Model (GCM) simulation at high spatial and temporal resolution that is designed to be as realistic as possible given present technological capabilities. The power of an OSSE is that analyses and forecasts from data assimilation can be compared to the nature run "truth" across many variable types and at many locations in space and time beyond simply what is observed. An OSSE can also be used to understand the added value of a new observing system in constraining the atmospheric state beyond that of existing observations. Therefore, designers of hypothetical new observations should be prepared to provide the following information: spatial and temporal coverage of observations, observation error estimates (e.g. error standard deviations, and any restrictions in coverage), and a forward operator that can be used to convert a GCM nature run into an observation.

Future Directions: Future capabilities offered by data assimilation include parameter estimation and the potential for weather forecasting. Parameter estimation is a powerful technique by which data assimilation can use observations to improve a model directly, and it has been applied to a variety of scenarios in terrestrial applications. For ensemble-based parameter estimation, the correlations between the observed value and the parameters are used to update the parameters in the model, using the premise that ensemble members that have a better parameter provide an overall better fit to observations; the key caveat is that the parameters are identifiable. For Mars, obvious candidates are parameters that the model is highly sensitive to during tuning. These include gravity wave drag parameters and CO2 and H2O ice albedos. Alternatively, one could estimate boundary conditions from their indirect impact on the atmospheric state. Here an important parameter is the surface dust lifting rate, which is not currently possible to measure, and is location- and season-dependent.

Finally, a cycling data assimilation system, linked to a skillful Mars numerical model and sufficient observation coverage, can form the basis for Mars weather forecasting. Such a system would be of value for EDL, rover operations, and future human exploration.

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