# Atmospheric Science Research Priorities for Mars

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A list of references for and signatories to this white paper may be found at http://mepag.jpl.nasa.gov/decadal/index.html

## Background

This white paper is a collaborative effort of the Mars atmospheric science community in order to outline its scientific direction for the coming decade (2011-2020) to the Space Studies Board of the National Research Council. This paper addresses one component of a two-part approach to the atmospheric exploration of Mars, divided along lines of surface lander (in situ) studies (see [1]) and orbital exploration. The text of Rafkin et al. contains all relevant discussion of the boundary layer, which we otherwise exclude here. Based upon solicited feedback from a wide range of contributors about the present and future direction of Mars atmospheric science, a consensus appears to be clearly emerging within the community, focusing on four Science Investigation Areas (SIAs) for future (continued) study. Among the input received, the following were the four SIAs most commonly cited:

1. Development of a network of surface landers to provide global, diurnal and synoptic coverage of the near surface environment, including interactions at the planetary boundary layer (PBL).

2. Development of a new program for the observation of atmospheric trace gases (e.g. $CH_4$, $SO_2$) including spatial/temporal distribution and relevant chemistry.

3. New campaigns to study previously underobserved parameters (e.g. winds) and atmospheric regions to augment continued observations of the basic atmospheric state (pressure, temperature, aerosol and water vapor abundance), which continues the long-term record of Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES), Mars Express (MEX) Planetary Fourier Spectrometer (PFS) and Mars Reconnaissance Orbiter (MRO) Mars Climate Sounder (MCS).

4. An interdisciplinary program to study the long-term climate and atmospheric/geologic record from Mars' past.

Discussion of SIA #1 (surface studies) is found in [1], while SIAs #2, 3 and 4 are found here. The discussion is divided into three sections, addressing the fundamental questions set forth by the SSB charter as they pertain to Mars atmospheric science:

1. What are the key scientific questions that will be driving Mars atmospheric science in the coming decade? What discoveries in the past decade have led us to these key scientific questions?

2. What progress can be made in the next decade to answer these questions?

3. What types of missions are necessary to obtain answers to these questions?

An effort has been made to highlight questions that are most *fundamental to advancing the science in the coming decade*. While there are many scientific questions having great merit on their own, we deal here with those that will provide the greatest advancement for the community as a whole. Key questions are highlighted and listed in priority order within each category.

## What are the key scientific questions that will be driving Mars atmospheric science in the coming decade? What discoveries in the past decade have led us to these questions?

***Trace Gases:*** Observations of Mars within the past several years have identified methane in the martian atmosphere, which will likely serve as the catalyst for a newfound emphasis on trace gas chemistry in the coming decade. The presence of methane, and potentially other trace gases (e.g. $SO_2$) that are not readily formed by martian photochemistry may reflect surface and subsurface processes previously unknown. Measurements by [2] reveal that methane varies on Mars with location and season, and provide a more convincing demonstration of the presence of methane than previous observations [3,4]. This variation is surprising since current photochemical models (e.g. [5]), which are successful in reproducing observations of atmospheric hydrogen- and oxygen-containing compounds, predict a 350-year lifetime for methane. However, the observed spatial and temporal variability suggests a much shorter decomposition lifetime. Other observations (ground-based and orbital) have yielded basic distributions of ozone [6] and hydrogen peroxide [7], allowing preliminary validation of first-order photochemical models.

As speculated by [2], the role of heterogeneous chemistry may be an important factor in the atmosphere (especially in controlling overall atmospheric chemistry), but one that suffers from a dearth of relevant observational data. Two roles for aerosols seem promising, complementary areas to explore. First, the lofting of soil and dust coated with strong oxidants (e.g. peroxide) may result in the rapid decomposition of many atmospheric species, including methane. Second, electrochemical processes that take place in dust storms can alter the homogeneous chemistry balance. Electrochemistry [8,9] has been speculated to be capable of producing hydrogen peroxide at levels up to 200 times the photochemically produced levels in the lower atmosphere, however little is known about the electric fields on Mars. Questions concerning trace gases in the atmosphere therefore include:

**Q1: What is the distribution and abundance of key photochemical trace species in the atmosphere (e.g. $CH_4$, $SO_2$)? What are their sources and sinks? Do they indicate the presence of life, currently or in the past? What role does the subsurface have on trace chemistry?**

**Q2: Is the composition of the atmosphere, both lower and upper, consistent with contemporary photochemical models? What does this tell us about processes (homogeneous or heterogeneous) that are missing?**

**Q3: What is the nature of the electric fields in the martian atmosphere?**

***Winds:*** There is surprisingly little observational data about martian winds, despite their critical importance in dictating the local composition and structure of the atmosphere, and their value for spacecraft safety. Descent profiles from past Mars surface payloads have provided a few, highly uncertain, wind profiles, while surface landers have provided qualitative measures of the surface winds over limited times and at fixed locations. Observations of cloud and dust devil movement provide supporting wind data. Knowledge of the 3-D wind field and its change over all timescales should be a critical component of any atmospheric survey, especially now that newer observational approaches (Doppler, sub-mm sounding) are available. Surface layer winds regulate the flux of water vapor and heat into higher levels. Tropospheric winds yield information about such varied elements as the strength of the martian tides, the state and strength of the global circulation and vapor and trace gas transport. The importance of understanding the wind field is illustrated by the efforts employed by spacecraft mission teams to constrain the wind field for entry, descent and landing (EDL) of spacecraft. Current knowledge of the wind field for these purposes is obtained exclusively from numerical models (GCMs and mesoscale models), and such models often yield vastly different wind profiles for the same locations. This underscores the need to have spacecraft data with which to validate the modeling assumptions being made. While models are useful for visualizing representative wind behavior, the absence of observational data ought to be corrected. Very basic questions concerning martian winds still remain, and include:

**Q1: What is the 3-D wind structure of the martian atmosphere from the surface to upper atmosphere? How does it change with time of day? Season? Interannually?**

**Q2: What is the strength of the global circulation? How does it change with season?**

***Dust:*** Mars is unique among the terrestrial planets in that solid material plays a significant role in modifying its climate. Dust lifted from the surface modifies the radiative environment of the surface and atmosphere, altering the thermal structure and changing the global circulation. There is seasonality to the martian dust cycle, with annually occurring periods of enhanced local and regional dust activity. Global dust events (GDEs) occur irregularly, but can envelop the entire globe with a thick cloud of dust in a matter of days [10]. We have learned recently through climate modeling activities [11,12] that a combination of convective processes (i.e. dust devils) and high threshold surface stress lifting are “triggers” that can initiate the spontaneous and interannually variable GDEs. Once initiated, these storms can grow quickly over time. The causes of such growth, and the factors that discriminate between regional and global storms, however, are unknown. Similarly, the means by which such events terminate are unidentified, although it has been suggested that a combination of particle settling and a change in the radiative environment introduced by the enhanced dust opacity itself (such that dust events may be self-limiting) may cause the ultimate demise of GDEs.

Limb profiles of dust abundance by TES [13] and MCS [14] have begun to resolve the vertical extent of dust in the atmosphere. Until recently, dust was considered to be well mixed in the lower atmosphere, with a rapid fall-off at higher altitudes (the so-called “Conrath” profile). This profile was (and is still) widely used by numerical models and for mission planning to simulate atmospheric dust profiles. Recent MCS observations, however, have shown more complex dust distributions that do not maintain this well-mixed character, though there is insufficient data to more fully characterize a ‘standard’ dust distribution, especially since both TES and MCS are unable to observe the lowest (<5 km) regions of the atmosphere. Establishing more representative dust profiles and dust abundances in the planetary boundary layer (PBL) will force reevaluation of standard circulation models to fit the improved observations, and thus facilitate better mission planning and protection of landed assets. The key questions about martian dust include:

**Q1: What is the vertical distribution of dust during local/regional/global dust events?**

**Q2: What are the root causes behind initiation, growth and decay of global dust events? Why do some storms remain small and some grow to global scale?**

**Q3: What are the impacts of the vertical, spatial and temporal distribution of the dust component of the atmosphere outside of dust storms?**

***Water:*** Recent estimates of the atmospheric water vapor column abundance by TES, MRO CRISM, and the MEX instruments (PFS, OMEGA, SPICAM), are leading to a generally consistent picture of the water vapor seasonal and spatial distribution. The globally average abundance of 10 prμm shows significant enhancements at high northern (~60 prμm) and southern (~30 prμm) latitudes during their respective summer seasons [15]. While the northern summer maximum shows high repeatability from year to year, the southern summer maximum is observed to vary in intensity by ~50% year to year, pointing to some as yet undetermined process regulating the southern hemisphere vapor cycle. A paucity of limb measurements of water vapor (and water ice) also means that the vertical distribution of these constituents remains largely unknown. General circulation models (GCMs) have difficulty reproducing the ebb and flow of the martian water cycle, which may be due to the absence of a subsurface water reservoir to interact with the PBL. Models (e.g. [16]) are able to attribute only a 1-2 prμm diurnal change to the adsorption of water vapor at the surface layer. Recent suggestions now point to the possible role of hydrated minerals on regulating atmospheric humidity. This issue remains unresolved and will require a combination of surface and orbital observations to resolve. Despite, or perhaps because of, decades of observations of atmospheric water, there are many unanswered questions about the water cycle. Key among these are:

**Q1: What is the abundance and variability of atmospheric water vapor on diurnal/seasonal/annual cycles? What factors contribute to these variations?**

**Q2: What is the vertical distribution of water ice and vapor in the atmosphere?**

**Q3: What is the role of the subsurface (regolith) on vapor abundance? What is the magnitude of the surface vapor flux on these timescales?**

**Q4: What is the role of water ice in the water cycle?**

***Middle/Upper Atmosphere:*** There has been an improved understanding of the dynamics and structure of the martian atmosphere in recent years, particularly from TES and MCS, but this knowledge is limited to regions from 10-80 km, which can be observed readily from orbit (see [17] and references therein). Numerical models, in conjunction with these observations, provide a reasonable approximation of the atmospheric state at locations and times not observed, but also highlight deficiencies in understanding the behavior of the martian atmosphere.

The past decade has seen new observations covering the middle martian atmosphere (60-130 km) by both MCS (<90 km) and SPICAM (70-130 km), and the first comparisons of such data with GCMs (e.g., [18],[19]), which have revealed significant discrepancies. While these new observations have the potential to answer important questions about this region of the atmosphere [20], there is still significant work still to do going forward. While the middle and upper atmosphere remain rather poorly observed, vastly improved numerical models—the primary means of understanding the behavior of these regions—are now being put to bear on these problems. The first surface-to-upper-atmosphere numerical models (e.g. [21],[22]) have been developed, and provide consistent model architecture at all levels. This is a significant step forward in modeling capabilities that will allow for more accurate modeling of the upper atmosphere, and which will continue to be refined in the coming decade. Aerobraking and entry, descent and landing density profile measurements (e.g. [23]) do provide additional, limited sampling of the atmosphere at levels above 100 km, and appear consistent with model results. The 2013 MAVEN mission will address this overall observational deficiency in part, but will also likely reveal patterns and behavior we cannot predict, especially at the higher altitudes, in regions influenced directly by the solar wind. Indeed, the previous NRC Decadal Survey [24] presented the following questions as having the potential for pivotal scientific discovery: 'What are the dynamics of the middle and upper atmosphere of the planet?' and 'What are the rates of atmospheric escape?', but due to an absence of relevant data in these areas, these remain key unanswered questions going forward, and are augmented by supplemental queries:

**Q1: What is the 4-D structure of the upper atmosphere (>120 km)? How does it evolve with the solar cycle? How does the atmosphere interact with the solar wind?**

**Q2: How do the middle and upper atmospheres behave as a system? How is this different from the lower atmosphere? How do processes in each affect the total system, and how well do our numerical models reflect this continuum of processes?**

***Atmosphere/Climate Evolution:*** There is substantial geological and chemical evidence that early Mars had a much warmer and wetter environment than the present. There are broad indications of aqueous alteration of surface materials dated to the Noachian period (4.5-3.8 Ga), including the widespread presence of iron-rich phyllosilicate minerals mapped to the oldest, Noachian-aged surfaces [25]. Today, there is only limited evidence of recent liquid water at the surface, which is likely transient in nature, and neither widespread nor enduring. It is almost certain that the atmosphere has lost mass over martian history, but how did it do so? Is atmospheric erosion through loss to space responsible? How secular or periodic would such change have been? Atmospheric erosion models can 'produce' multi-bar $CO_2$ atmospheres on early Mars that are consistent with today's thin atmosphere and contemporary isotopic ratios. Conversely, there are suggestions that much of the primitive atmospheric $CO_2$ has been converted into subsurface carbonates, and/or buried as $CO_2$ ice or $CO_2$-clathrate ice. Understanding the climate system as a whole (including the surface and subsurface environments) is key to extrapolating backwards to previous epochs, and presents us with several unanswered questions:

**Q1: What atmospheric conditions would sustain liquid water at the surface during early martian history?**

**Q2: What are the isotopic ratios of the most common gases? What does this tell us about atmospheric erosion rates and the possibility of life, past or present?**

**Q3: What are the rates of atmospheric escape out the top of the martian atmosphere? Are current erosion processes consistent with a substantially thicker early martian atmosphere that has progressively eroded to the present, thin state?**

**Q4: Is there an observable, secular or periodic change in martian climate (e.g. temperature, atmospheric opacity, water content) over extended periods?**

## What progress can be made in the next decade to answer these questions? How?

Mapping the composition and state of the martian atmosphere can be accomplished in the coming decade by pursuing a multi-pronged approach to observing the atmosphere, including: 1) Characterizing boundary layer fluxes of atmospheric components, especially across the surface layer. This includes tracking the annual cycle of $CO_2$ into and out of the atmosphere at several surface locations, stable noncondensable gas (Ar and $N_2$) enrichment levels and the diurnal, seasonal and annual cycle of $H_2O$ and trace gas exchange between the atmosphere and regolith. 2) Continued observations of the atmosphere from orbit to map global pressure, temperature, aerosol opacities, winds and other components from the surface to upper atmosphere, with greater vertical resolution and time of day coverage. 3) Development of instrumentation (surface and orbital) for the detection and identification of small amounts of trace gases and their isotopologues down to the parts-per-trillion level. 4) First steps to observe the 3-D wind field by the end of next decade. For boundary layer winds, 3-D, high frequency surface measurements are ideally required, while at higher levels, winds can be extracted from remote sensing approaches. Newer techniques can provide wind measurements across the globe, including regions (such as those obscured by dust), which have been inaccessible to previous remote sensing instruments. 5) Combining limb and nadir observations of dust to answer questions pertaining to the 3-D dust distribution, the growth and decay of storms and the transport of dust, water, and trace gases.

To supplement these measurements, advances in modeling (i.e. GCM) capabilities can further assist in tracking atmospheric composition including trace gases. Within the next decade, investigations designed to identify trace gas source regions should be undertaken, as these will likely drive site selection for future landed missions. Data assimilation approaches (e.g., [26]), still at a nascent stage, should help to improve the accuracy of GCMs by blending temperature and dust opacity data (derived from observed radiances) with model predictions. Better-validated models will also improve isolation of trace gas source regions.

It is becoming clear many of these questions are not exclusive to the atmospheric community alone, and answering them will require the collaborative efforts of the broader Mars community. Interpreting the recent discovery of methane plumes, for example, is equally a problem of meteorology, geology and astrobiology. By treating Mars as a unified, and interconnected, system, we can best address these problems.

## What types of missions are necessary to obtain answers to these questions?

To maintain a continuous seasonal climatology of temperature, dust, ice opacity, and the general atmospheric state, it is necessary to obtain these data by *habitually* flying instrumentation with capabilities at least comparable to past and present missions and should minimally include the means to observe in the dust, water ice and $CO_2$ absorption bands with moderate-to-high spectral resolution. Observations higher in the atmosphere, at levels where spacecraft aerobraking and aerocapture occur, are desirable as well, and instrumentation should be capable of providing, at minimum, measurements of atmospheric density. Such instruments must have both zenith and limb-scanning capabilities in order to provide both aerosol and thermal profiles and total column opacities. Greater coverage in local time—an improvement over past and present observations—is needed to better characterize wave modes and diurnal variations of water vapor and ice clouds. These types of measurements should be baseline requirements for future missions, and can easily fly as a valuable component of a larger (e.g. New Frontiers, Flagship) payload. Simpler payloads, containing only portions of the instrumentation described above, are valuable assets for smaller Discovery-class missions, and should fly at every available opportunity.

The overarching goal of a future trace gas survey should be to seek atmospheric evidence for present habitability and life through a sensitive and comprehensive survey of the abundance and temporal and seasonal distribution of atmospheric species and isotopologues. To achieve the objectives of such a survey requires a coherent set of instruments, on both surface and orbital platforms, some with capabilities not previously flown to Mars. These should include remote sensing instrumentation with extremely high sensitivity to a broad suite of important trace gases combined with nearly continuous spatial mapping of key minor constituents and of atmospheric state including vertical profiles of atmospheric temperature and aerosol abundances. Atmospheric observations should include a baseline set of molecular species necessary to isolate the key photochemical, transport, condensation, and biogenic-geochemical processes that control the current chemical state of the Mars atmosphere. In many cases these observations will require exceptional sensitivities relative to prior mission capabilities. An orbit should be chosen to allow an optimum combination of global coverage, spatial resolution, and a rapid change of local time during the course of the mission. A lifetime of at least one martian year is necessary to observe the annual cycle, with the possibility of additional martian years highly desirable for assessing interannual variations.