The Value of Landed Meteorological Investigations on Mars: The Next Advance for Climate Science

For Consideration by the National Research Council Space Studies Board in the Development of the Next Planetary Science Decadal Survey

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1 The Case for Mars Surface Climate Investigations

Complementary whitepapers submitted for consideration by the Decadal Survey Committee make the case for Mars as a high-priority exploration target[1] and for Mars climate investigations in particular[2]. In this paper, we argue that major advances in the understanding of the present and past Mars climate system are most likely to be accomplished by in situ meteorological surface measurements operating from both a network configuration and individual stations. Support for this position is based on the scientific output from past and ongoing Mars atmosphere measurements, reasonable expectations of future orbital information, the unique science enabled only by atmospheric measurements made at the surface of Mars, and the nature of the key outstanding climate science objectives, as identified by the Mars community.

The National Research Council Space Studies Board Committee is urged to recommend that all future landed Mars missions carry a capable meteorological investigation and that the recommendation for a Mars meteorological network as a high priority mission within NASA's Mars Exploration Program be retained from the previous Decadal Survey.

Over 30 years ago, the Mars Viking Landers obtained the first *in situ* meteorological observations on the surface of a planet other than Earth. From these simple data, a great deal was learned[3,4,5,6] about the weather and climate of Mars, including the identification of a strong seasonal cycle of CO_2, the existence of extratropical storm systems similar to those on Earth, and the documentation of a large amplitude thermal atmospheric tide. Although surface meteorology investigations were later conducted by the Pathfinder[7] and Phoenix[8] missions, these data lack the time coverage needed to document the strong seasonal cycles and climate of Mars, and many of these data suffered from calibration problems, limited sampling, or sensitivity.

Numerous orbiting spacecraft have also provided a wealth of information on atmospheric state. The most groundbreaking information was obtained by the nearly three Mars years of vertical temperature profiles and column water vapor, ice, and dust opacity data acquired with the Thermal Emission Spectrometer (TES)[5].

Meteorological measurements at the surface of a planet provide information that is difficult, if not impossible, to obtain from orbit. It is at the surface and within the planetary boundary layer (PBL) immediately above where there are large exchanges of heat, momentum, dust, water, CO_2, CH_4 and other volatiles. It is at the surface where the weather shapes, through aeolian processes, the surface of contemporary Mars. The processes operating at the surface and within the planetary boundary layer are the engines that drive the climate and constantly modify the geological landscape. To understand how the current climate system operates, it is necessary to understand the climate engine. And, to understand why Mars' past climate may have been warm and wet, or to understand how it evolved to its present state, it is necessary to understand how the present state works. *In situ* surface measurements are the underpinning to this understanding, and for the most part, none of these measurements can be made from orbit. Looking holistically at the history of Mars atmospheric measurements both from orbit and from the surface, it is clear that there is a significant and substantial lack of information about surface meteorology and the processes operating at the surface-atmosphere interface and within the PBL.

Surface measurements are advantageous compared to satellite-derived data. First, geo-asynchronous satellites are unable to provide a continuous time series of measurements for a given location. Limb data is somewhat helpful in this regard, but past, present and planned Mars orbiters are unable to obtain anything close to continuous full time of day coverage.

Second, satellite retrievals often require complex inversions of measured radiance. Just as models need to be validated by observations, remotely sensed quantities based on radiative transfer models also need to be validated. Surface measurements provide both a convenient lower boundary condition for atmospheric retrievals and a validation point.

Neither nadir nor limb retrievals satisfactorily provide local information of surface meteorology and processes, and neither method provides synoptic coverage. Without *in situ* measurement, the Mars climate picture of both past and present will remain incomplete. The need for surface measurements remains as strong as it did prior to the last Decadal Survey.

2 Traceability of Surface Science

The Mars Exploration Program Analysis Group (MEPAG) has identified a prioritized list of science objectives and investigations under the Mars Climate Goal[12]:

MEPAG Climate Goal: Understanding the Processes and History of Climate on Mars.

Highest Priority Objective

Characterize Mars' Atmosphere, Present Climate, and Climate Processes Under Current Orbital Configuration

Highest Priority Investigation

Determine the processes controlling the present distributions of water, carbon dioxide, and dust by determining the short- and long-term trends (daily, seasonal and solar cycle) in the present climate…

There has yet to be mission dedicated to the first half (lower atmosphere) of this highest priority investigation[13]. None of the previous landing sites (VL1, VL2, Pathfinder, Phoenix) were driven by climate science or maximizing climate science return. The same is true for the upcoming MSL mission. Of all the recommended missions within the last Decadal Survey[14], the Mars Meteorology Network mission, which would have substantially addressed the MEPAG goal, has gone mostly ignored.

It is said that, 'climate is what you expect while weather is what you get.' Climate is the long term value, trend, and variance of weather, and has properties that vary in space and time on scales that range from local (microscale) to global (planetary-scale) and from seconds (*e.g.,* turbulent eddies) to years (*e.g.,* climate change). Thus, to capture the climate, it is necessary to measure the weather at appropriate spatial and time scales. Long-term, global, and high frequency measurements are, therefore, a necessity.

The role of surface measurements in relation to the understanding of climate processes is through investigations of the CO_2, H_2O and dust cycle, which involve the exchange of heat, mass, and momentum between the atmosphere and surface, and the variation of these processes around the planet and over time. MEPAG has explicitly recognized this, as illustrated by the narrative discussing the highest-priority climate investigation[12] and the unique contribution from *in situ* measurements at the surface.

To date, emphasis has been on orbital measurements that have done a good job of characterizing the bulk atmosphere and climate, but cannot see the surface where exchange with the atmosphere occurs. Therefore, landed missions are required to complete the characterization of the climate system.

FINDING
Orbital retrievals are valuable, but are not a substitute for *in situ* measurements. There is high priority science that is best achieved or can only be achieved from the surface.

3 Implementation Strategy

The only way to address the highest priority investigation *with a single mission* is to establish a long-lived global network capable of measuring a variety of fundamental parameters (*e.g.,* T, p, relative humidity, winds, dust) and fluxes of these quantities with the global monitoring support of one or more orbital assets.

FINDING
Regardless of the mission architecture the dynamic range of the climate system mandates that the full achievement of the highest priority MEPAG Climate Science Goal and Objective will require long-term, global measurements.

The CO_2, water, and dust cycles are all of global extent, and monitoring requires global coverage. Using general circulation model output to estimate the number of stations required to accurately determine the global mass of the atmosphere, a minimum of 16 stations, roughly equally spaced over the planet, are required to substantially reduce the root mean square error in estimates of the surface pressure distribution.[15] Therefore, a notional number of stations for a global network is ~20. With further study, and given the convergence of meridians in the polar regions, it may be possible to decrease this number by a few stations.

FINDING
A global meteorological network designed to address the global MEPAG climate objective requires ~20 nodes.

Given the reality of limited available resources and the state of technology, the best strategy for achieving the MEPAG science goals with surface investigations consists of two parts. The first part is to ensure that every future lander carry meteorological payloads that can begin to address the highest priority MEPAG climate investigation. Operating under this strategy, the payload should be sufficient to fully characterize exchange processes (*e.g.,* fluxes) at a limited number of sites. The resulting data can then be used to infer exchange processes from a global, but likely less sophisticated and capable network investigation. The second part is to work toward the implementation of such a global network. This strategy is realizable in the next decade.

Embedded within this strategy is the assumption that, under realistic scenarios, the trade between a few meteorological stations versus a network is likely to be one of sophistication versus number. Non-network missions, because they have fewer landers, could carry more sophisticated payloads, measuring parameters beyond the core pressure, temperature and winds. A network, even though potentially less (perhaps measuring only core meteorological parameters) provides information about the variability and diversity of climate processes for which even a fully equipped single lander is not capable. Network and non-network missions are highly complementary and both are required to achieve the high-priority science goals identified by the community.

There are many types of meteorological payloads worth flying on single or multiple lander non-network missions. Investigations addressing the global mass balance, local circulations, the planetary boundary layer, aeolian processes, and the exchange of heat, momentum, and water between the surface and atmosphere are all feasible from a single station.

We presently have limited meteorological data from four sites (VL1, VL2, Pathfinder, and Phoenix) widely separated in time and space, and these have provided a glimpse at a small sample of the rich diversity of meteorological regimes that surely exists around the planet.

Missions with a limited set of landers could, in principle, address mesoscale phenomena such as frontal structure[16], local dust storms[17,18], polar lows[19], gravity wave excitation[20,21,22], and bore waves[22]. Thus, payload sophistication is an advantage for non-network missions that can enable fundamental new and important measurements.

Recognizing that resources can be limited even on single lander missions, there is a hierarchy of possible payloads each of which can contribute to our understanding of atmospheric science at Mars. The simplest useful investigation that could be addressed with a single lander is the global mass balance, which requires the measurement of only one parameter: surface pressure. Surface pressure varies not only because of meteorology, but also because the main atmospheric constituent of the Martian atmosphere (CO_2) alternately condenses and sublimes in the polar regions. Thus, surface pressure records the heartbeat of the climate system and, because pressure sensors are light, require little power, and do not need orientation or deployment, they should form the core of any landed meteorology package. Pressure is the highest priority measurement.

Air temperature is also relatively easy to measure, and it provides information about the thermal environment, water and CO_2 volatility, and even the atmospheric dust loading which modulates the diurnal cycle. Thus, air temperature should also be included, along with pressure, as part a basic meteorology package for future Mars landers.

However, the next major increase in our understanding of the near surface environment will come from high quality systematic measurements of winds. For this reason, winds are the next highest priority for any landed meteorology payload after pressure and temperature. Surface fluxes are major forcing functions of atmospheric motions yet very little is known about their magnitude and variability; fluxes require the high frequency measurement of the vertical wind[23]. To maximize return, these measurements should be made at two or more heights. Thus, even a single lander measuring pressure, temperature, and winds would acquire fundamentally new and important data.

After the core parameters of pressure, temperature, and wind, are simultaneous measurements of dust and moisture concentrations that permit the direct *in situ* determination of local sources and sinks of these quantities. The seasonal dust cycle has a strong influence on atmospheric circulations and therefore controls how material is transported around the planet;[24,25] yet, the conditions that enable lifting off the surface and injection into the atmosphere are poorly understood. Wind measurements coupled with simultaneous particle concentration measurements would enable the determination of the threshold stress required for lifting[26]. This has yet to be done for Mars and it can only be done from the surface.

For water, there is still uncertainty about the role of adsorbed water in the regolith and/or ice beneath the surface[27,28] that could be explored by near-surface vapor measurements. Such measurements would enable the determination of the direction, magnitude, and diurnal phasing of vertical vapor fluxes, which can be related to that nature of surface reservoir.

Other important measurements yet to be made at the surface are the downwelling infrared radiation and total solar flux. The net radiative flux at the surface is the primary driver of the climate system and when coupled with surface turbulent fluxes would allow full characterization of the boundary forcing.

It should be clear from these discussions that there is great value in surface meteorological measurements from a single lander, or from a multiple set of landers too few in number to constitute a true meteorological network. Furthermore, these measurements address fundamentally important processes that are active on Mars today, have not yet been measured, and are not merely a repeat of earlier weather observations. The Martian climate system is process driven and spatially diverse.

FINDING

Given the mature state of meteorological instruments, their technical readiness (most are at or above TRL 5), low cost, relative ease of implementation, and high value to science and engineering, credible meteorological instruments must be part of every future landed package to Mars.

There has been much confusion over what constitutes a meteorology network. A network must have a sufficient number of nodes so as to conduct network science. Anything less is not a network, but a collection of simultaneously operating stations.

At a recent Mars Meteorology Workshop[29], consensus was reached among stake holders using a practical definition for a network: a network provides information and science not attainable by the measurements of the nodes taken individually. Network science is achieved by combining node measurements to create information that could not otherwise be attained through individual measurements, by analyzing network measurements to identify patterns and spatial distributions, or by acquiring simultaneous measurements of similar quantities in order to improve the signal-to-noise ratio.

As previously indicated, the ideal network would consist of dozens of long-lived nodes with highly capable instruments similar to the payload desired on a single station lander. Realistically, a network will likely be much less capable. Thus, the role of the individual stations is to provide details on the complex processes operating at a limited number of locations on the planet while the role of the network is to obtain a diversity of simultaneous measurements to obtain context for the surface (and orbital) measurements, to extend the local information to the global scale, and to obtain information meaningful only on a global scale.

The global CO_2 cycle produces the strongest climate signal on Mars in the form of the large seasonal variation of surface pressure. Pressure is the primary quantity of interest in studying the CO_2 cycle, since it is tied directly to the mass of the atmosphere, which is predominately CO_2. One of the outstanding questions about the CO_2 cycle is whether the atmosphere is undergoing secular climate change and what the magnitude of interannual variability of the climate is. Accurate, networked measurements of pressure over several seasonal cycles would be able to make this determination. A single station measurement of pressure could also make some strides in constraining the atmospheric mass balance, but the seasonal variation of pressure will differ from one site to another due to variations in the general circulation[15]. Therefore, a collection of simultaneous measurements are needed to truly separate out the global effects from the local effects.

"Follow the water" has been the mantra driving Mars exploration for well over a decade. It is not known whether the current water cycle is in equilibrium. Modeling studies are unable to produce a balanced water cycle, and instead tend to show a net accumulation of water at the south pole at the expense of the north water ice cap[30,31]. Variations in obliquity almost certainly provide a forcing mechanism that drives the water cycle towards different equilibrium states that may include water ice stability in the tropics[32]. Therefore, the present reservoirs of water on Mars are time capsules, containing information about previous orbital configurations, and, the atmosphere, being the primary reservoir exchange mechanism at present, controls the rate which the reservoirs respond to the obliquity changes.

The lack of information and understanding about the contemporary water cycle on Mars makes it extremely difficult to rewind the clock and then understand how the water cycle operated thousands, millions or billions of years ago. Observations from present-day Mars permit the development and testing of hypotheses that can explain the behavior of the global water cycle. Armed with this knowledge, it becomes a more tractable problem to determine how these same processes may have operated in the past, or how the relative importance of processes may have changed over time.

Atmospheric dust, through its radiative effects, is a primary driver of the circulation on contemporary Mars. Planet encircling dust storms are also one of the most widely recognized phenomena associated with the planet. Furthermore, for at least the last several billion years, the dominant process shaping the surface of Mars has likely been erosion through aeolian processes. Therefore, a greater understanding of the dust cycle and dust lifting processes is a critical element to understanding the present-day climate and to understanding how Mars evolved to the present state. A well dispersed global network of stations would provide information on the disturbances that lift dust (e.g., fronts, katabatic winds). And, a modestly equipped network might finally provide insight into what produces global dust storms, how the storms are maintained, and how the initial disturbance is globally communicated to activate lifting at geographically distant locations (so-called teleconnection). A network might also identify any precursor signatures to the onset of these storms[33].

FINDING

Meteorology should remain as a high-priority Mars network investigation, as it was in the previous Decadal Survey.

4 Support for future missions

The benefits of meteorological surface measurements go beyond science. *In situ* surface information is vital to the validation and improvement of the atmospheric models that are used to predict the environment for Mars spacecraft. And, as described in the MEPAG Mars Human Precursor Measurement document, monitoring of the lower atmosphere is essential for the safety of humans, and for safe operation of the robotic components needed to support human exploration.

Beginning with the Mars Exploration Rovers, substantial effort has gone into characterizing the lower atmospheric environment for entry, descent, and landing for spacecraft landing on the surface. Due to lack of data, these efforts have relied almost exclusively on the use of models[34,35]. Surface measurements are needed to validate the models. If the atmospheric environment were better known, costs would be reduced by eliminating over-engineering, and additional resources could be made available to the scientific payload so as to increase the scientific return per taxpayer dollar.

FINDING
Networks provide a major risk reduction and cost reduction benefit to future missions by better constraining the environment and improving environment predictions.

5 Current and Needed Technology

The instrument technology for measuring basic meteorological parameters is mature at TRL 6-9. New, more advanced, accurate and robust methods that enhance these existing measurement techniques are currently under development. Compared to typical Mars instrumentation, all of these sensors are low power and low mass. And, when compared to the spectrometers, composition analyzers, and other *in situ* instrumentation that have been deployed on past landers, meteorological instrumentation is also low risk, low cost, relatively easy to accommodate, and operates with a low data rate.

FINDING
Core instrumentation for a meteorological station is mature and ready for flight. Advanced instrumentation is relatively advanced and can be credibly proposed.

Beyond the floor instrumentation for a meteorological mission, there are numerous supplementary, modest TRL payloads that would enhance a mission. These include electromagnetic sensors, flux radiometers and dust optical depth sensors, and instruments that characterize the size distribution of dust.

The major challenges with surface measurements are not primarily in the instrumentation, but in the implementation of the architecture. How are the probes properly oriented for measurement upon landing? How is power provided at high latitudes and over long, perhaps multiannual, periods? In the case of networks, how are over a dozen probes launched, deployed, and successfully landed and how is communication between numerous nodes and an orbiter achieved? If a meteorology network mission is to fly, the major technical issues need to be addressed in some manner. This is particularly necessary in order to obtain an accurate cost and risk estimate.

NASA has provided little to no focused support of projects that would help to reduce the risk of, and advance the technology for, network missions. Nuclear power sources in the 1-10 W range are needed for long term and high latitude meteorological stations, as are small probe EDL and deployment technologies. A commitment to a network by NASA should include resources to advance these technologies.

FINDING
Additional network technology development is needed, primarily in the areas of power, EDL, and communication.

6. International Cooperation

The history of Mars network science efforts demonstrates strong interest by the European community. A network mission is well suited to international cooperation, because the mission elements can be easily separated. A partnership that makes use of the strengths of the global community is cost-effective approach and might accelerate network mission endeavors. Leveraging global technology would almost certainly reduce the cost of a network mission to NASA.

FINDING
NASA should engage with foreign space agencies to enhance scientific expertise, leverage mutual technology development, and to reduce the overall cost to any one agency.

8. Summary

Surface meteorology measurements have not been given priority in the exploration of Mars over the last several decades. However, there are high-priority science objectives and investigations that have been identified by the community for which such measurements are essential. A long-lived, highly capable, global network is needed to achieve the science within a single mission. However, individual highly capable meteorological stations flown on every future mission coupled with a global network of core meteorological measurements would also make great strides toward the scientific objectives, and this implementation strategy is realistic.

FINDING

The National Research Council Space Studies Board Committee is urged to recommend that all future landed Mars missions carry a capable meteorological investigation and that the recommendation for a Mars meteorological network as a high priority mission within NASA's Mars Exploration Program be retained from the previous Decadal Survey.

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