MEPAG

Report from the Ice and Climate Evolution Science Analysis group (ICE-SAG)

FINAL VERSION – July 8, 2019

Recommended bibliographic citation for this pre-print draft:
MEPAG ICE-SAG Final Report (*2019*), Report from the Ice and Climate Evolution Science Analysis group (ICE-SAG), *Chaired by* S. Diniega and N. E. Putzig, 157 pages posted 08 July 2019, by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm.

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Colin Dundas	US Geological Survey	subsurface ice, surface activity, geomorphology
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Contents

Executive Summary

This document is the final report of the Ice and Climate Evolution Science Analysis Group (ICE-SAG) that was formed by the Mars Exploration Program Analysis Group (MEPAG) as part of its preparations for the upcoming NASA Planetary Science Decadal Survey for 2023 through 2032 (see §1). Through telecons, one face-to-face meeting, and discussions with experts in relevant topics, ICE-SAG has identified high-priority science questions and key measurements that are needed to address them as well as the 2018 MEPAG Goals and the 2013-2022 NASA Planetary Science Decadal Survey goals [V&V, 2011] pertaining to ice[1] and climate. Obtaining these measurements would yield dramatic improvements in our understanding of the climate history of Mars, which is critical to investigations of Martian geologic history and habitability and will also inform the potential of buried water ices as in situ resources for future human missions. In many ways, the Martian climate system serves as a laboratory for a broader understanding of planetary climate systems including the Earth's, which is substantially more complex due to a denser atmosphere, a more active planetary interior, and interactions with oceans and abundant life, while operating under much more subtle orbital forcing. Thus, advancements in Martian climate science will have far-reaching impacts that extend to studies of the Earth and other planetary bodies.

Key points from this study, summarized within the ICE-SAG findings, are listed in Table ES.1 in the order that they are presented and discussed in greater detail throughout the report. ICE-SAG considered the current state of knowledge (§2) and how recent scientific discoveries have refined the questions about Martian ice and climate (§3) that inform high-priority investigations of Mars climate science. An overarching goal of understanding the climate record leads to the need for addressing many interconnected questions about the state of volatiles, their fluxes between reservoirs (especially ice reservoirs), and the associated drivers and processes. The effort to address those questions will require a broad range of measurements, including those related to atmospheric transport of materials, current distribution of volatiles, structure and composition of ice deposits, formation of ice-rich layers, the presence of liquid water, habitable environments, and resource potential. These considerations fed into mission concepts listed below and discussed in detail in the report (§4). Existing or expected technology advancements to enable access to the Martian surface and subsurface and the operation of spacecraft in extreme environments make these concepts feasible (§5). Achieving the needed measurements can be further facilitated by investing in laboratory work, numerical modeling, and field studies that address critical gaps in knowledge (§6).

The compelling, high-priority science questions concerning Martian ices and climate presented in this report (§3) are addressable in missions that are feasible within the next decade. Given the breadth of the measurements needed, no single mission can address them all, but even a single mission may address many of them and yield major advancements in our understanding of Mars' recent[2] climate history. The ICE-SAG discussed a range of mission concepts spanning all mission

[1] The terms "ice" and "frost" refer to both water ice and carbon-dioxide ice unless otherwise indicated.

[2] We take as "recent" those Amazonian climate periods potentially recorded in polar and non-polar icy layers. This is consistent with usage of "recent climate" in the Decadal Survey: "For modern and transitional (recent) Mars time frames it appears that the climate was periodically different from what it is today because of the oscillations of Mars orbit and rotation parameters" [V&V, 2011: p6-11].

sizes, classes, and architectures that would collectively address all high-priority science questions. As part of this report (§4), we present five example concepts that we believe are realizable within the cost-cap of NASA's New Frontiers Program:

1. A polar lander to investigate the upper 1 m or more of northern layered structure
2. A polar lander to make in situ observations of the seasonal frost[1] layer
3. An orbiter and small lander(s) to carry out meteorological monitoring
4. A lander to investigate vertical structure of mid-latitude water ice
5. An orbiter to map the distribution, structure and activity of near-surface ices

Each mission concept addresses a unique set of key ice and climate questions and could in principle be carried out independently of the others, so ICE-SAG chose to assign no priority ranking among them. In addition, we discuss options to expand or reduce these concepts for other mission classes, and we describe a few smaller stand-alone mission concepts. These example concepts demonstrate that there are multiple feasible ways to address key ice- and climate-science questions in the next decade.

Table ES.1 ICE-SAG Findings

Finding # / Section # & title	**Finding**
1 / 2 Current State of Knowledge	Recent discoveries and studies of Mars' ice reservoirs have significantly changed our views of ice occurrence on Mars, its role in driving surface and subsurface processes, its implications for astrobiological studies, and its potential for in situ resource utilization. These advancements enable a new definition of investigations that would make key measurements to provide a new understanding of these records of the recent climate of Mars.
2 / 3 Compelling Questions & Priority Science Areas	Understanding the record left by the recent Mars climate requires investigation of interconnected questions involving ice volume and state, fluxes, drivers, and processes.
3 / 3.1 Priority Science Area A: Transport of volatiles and dust into & out of ice reservoirs	Precise measurements of the transport of materials through the Martian atmosphere and between the atmosphere and surface/subsurface are key for determining how volatiles and refractory materials are moving into and out of the polar regions and how vertical structure forms within ice reservoirs. Simultaneous measurements of winds, the water mixing ratio (or absolute humidity), temperature, pressure, net radiation balance, and dust concentration, at the surface and within the atmospheric boundary layer, are crucial missing data that are needed to address these questions and to characterize the present climate.
4 / 3.2 Priority Science Area B: Global	Measurement of the spatial distribution and volume of non-polar subsurface ice deposits, along with the depth to ice, is key for determining the total volatile inventory on Mars, where ice may be stable in the present climate,

distribution & volume of subsurface ice	and how it has been retained in locations where it is thought to be unstable. A primary need is the mapping at sub-meter-scale resolution of the near-subsurface within the uppermost 10 m.
5 / 3.3 Priority Science Area C: Vertical structure within ice reservoirs	Mapping the structure and measuring the composition and properties of the layers within ice reservoirs is key for quantitatively determining the climate conditions throughout the record of climate history of Mars. Investigation of the vertical structure of the ice reservoirs can be done broadly via high-resolution orbital radar sounding, or locally via ground penetrating radar or drilling into the layers. The in-situ measurements enabled by drilling would yield characterization of fine layers that we expect to reflect the accumulation history of volatiles and refractory materials. A combination of these investigations, along with laboratory and modeling studies of processes, are needed to connect present-day observations and seasonal processes with the cumulative record of processes and conditions (including through climate shifts) in the layers.
6 / 3.4 Priority Science Area D: Formation conditions & processes for ice reservoir layers	Identifying which ice reservoirs may be currently growing and determining how a layer forms are critical for enabling interpretation of the layers as records of past climate. Measurements of the annual deposition of frost and refractory materials, determination of how those materials are incorporated into the surface, and identification of what may be retained before the next winter cycle are necessary at both local and regional scales and over daily through annual cycles.
7 / 3.5 Priority Science Area E: Potential evidence of liquid water	A key open question remains regarding the possibility of mid- or low-latitude liquid water at or near the surface in the present or recent climate, despite many relevant studies. Laboratory and modeling work to better define conditions under which liquid occurs and to quantify the amounts expected to create observable chemical or geomorphological changes are needed. Results would guide future investigations, which may be based on both updated analysis of current Mars datasets and on new in situ or orbital observations of a potential liquid-water driven surface activity.
8 / 3.6 Relationship of Priority Science Areas to Astrobiology	Science investigations of ice and climate on Mars would yield important insight into environments that may be or may have been habitable. Additionally, for investigations that involve direct contact with ice reservoirs, there may be synergies with the search for evidence of extant or past extraterrestrial life and planetary protection concerns.
9 / 3.7 Relationship of Priority Science Areas to Human Exploration Interests	Measurements addressing high-priority Mars ice- and climate-science investigations have major implications for in situ human exploration. In particular, detection and characterization of near-surface ice reservoirs are of keen interest for potential in situ resource utilization, although human proximity to ice-rich locales has implications for planetary protection. Additionally, many high-priority surface and atmospheric measurements would yield important inputs for understanding the hazards associated with

	dust and other windborne risks.
10 / 3.8 Tracing to MEPAG Goals	Key measurements addressing high-priority science questions relevant to ICE-SAG and the 2018 MEPAG Goals would yield substantial advances to our understanding of recent Martian climate history and resource potential of Martian ice.
11 / 4 Mission Concepts to Address Key Ice and Climate Science Questions	Compelling, high-priority Mars ice- and climate-science questions concerning Martian ice and climate are addressable by mission concepts that are feasible within the next decade. These mission concepts span a range of mission-sizes/classes, and architectures.
12 / 4 Mission Concepts to Address Key Ice and Climate Science Questions	Five mission concepts larger than NASA's Discovery class have been identified that would address high-priority Mars ice- and climate science questions. These concepts appear feasible in the next decade but have remaining technological and costing questions. A detailed costing and technology development study of these mission concepts, or other concepts aimed at achieving similar measurements, would address these questions and contribute important information to a discussion of compelling potential Mars missions in the next decade.
13 / 4 Mission Concepts to Address Key Ice and Climate Science Questions	Smaller mission concepts (i.e., Discovery-class or "small spacecraft") could address subsets of the high-priority ice- and climate-science questions, while still making significant advancements of our understanding of the recent Martian climate.
14 / 4 Mission Concepts to Address Key Ice and Climate Science Questions	Each mission concept presented addresses a different subset of the key Mars ice- and climate-science questions. Certain aspects of these concepts could benefit from running some missions concurrently or in a certain order. For example, carrying out the orbiter concepts first could facilitate choosing sites for the landed ones, although such reconnaissance could instead rely upon current data or data being acquired by the ongoing missions at Mars. However, there are no explicit interdependencies between the concepts and each one could in principle be carried out independently of the others. Each mission concept would contribute meaningfully to high-priority Mars ice and climate science.
15 / 5 Key technology challenges and constraints on	Key areas of technology development would enhance or enable acquisition of needed measurements. These include technologies to address surviving the polar night, avoidance of surface contamination as well as subsurface contamination while acquiring samples, landing in the poles at a specific time

Ice & Climate focused Mars missions	of year, and reduction in the cost of delivering payloads to the Martian surface.
16 / 6 Key complementary studies for Ice & Climate focused Mars missions	Laboratory, modeling, and field studies were identified that would enhance acquisition and interpretation of needed measurements. These include investigations of CO_2 frost evolution, water interaction with Martian regolith, variation of material properties with regolith composition, the relationship between Mars' radiative balance and atmospheric processes at local and regional scales, and analog studies of terrestrial ice cores and climate records.

1 Purpose and structure of ICE-SAG

In October, 2018, the Mars Exploration Program Analysis Group (MEPAG) Executive Committee chartered this Ice and Climate Science Analysis Group (ICE-SAG) as part of their Mars community preparations for the next Planetary Science Decadal Survey (Appendix A). The main aim of this SAG was to identify and prioritize fundamental science questions related to the recent and ongoing evolution of Mars volatiles and climate, and to explore new mission approaches that could address these high-priority science questions during the coming decade (2023–2032).

1.1 The Importance and Timeliness of Mars Ice and Climate Science Investigations

Mars has a complex history of climate variations over long and short timescales. As impacts and volcanism have waned, processes related to frost and atmosphere have become the dominant forces shaping the surface during the Amazonian period. The current Planetary Science Decadal Survey (*Visions and Voyages*, hereafter referenced as V&V [2011]) identified the processes and history of climate as one of the three most important goals for Mars science (Committee on the Planetary Science Decadal Survey, 2011), and questions related to climate are vital to addressing the two other top priorities: the possibility of life, and the evolution of the surface and interior. The Decadal Survey also distinguished between modern, recent, and ancient climate; the ICE-SAG study focused on the modern and recent Martian climate, where "recent" consists of Amazonian periods preserved in polar and non-polar icy layers, which are driven by changes in obliquity and other orbital parameters.

The fundamental components of the recent Martian climate system are CO_2, H_2O, and dust [V&V, 2011]. On timescales from seasons to orbital variations over millions of years, these are the key drivers of the atmospheric circulation, the agents that reshape the surface, and the material that comprises the climate archives in their deposits. All aspects of this system vary on diurnal, seasonal, and interannual time scales in ways that we are just beginning to characterize. As will be described in this report, recent discoveries have revealed many pieces of the modern and recent climate system and their effects on the surface. The discoveries have both shown surprising complexity and opened the door to new breakthroughs in addressing this fundamental objective.

In particular, within the last decade, the discovery of new ice (CO_2 and H_2O) reservoirs, and new information about their distribution and stratigraphy, has led to improved interpretations and hypotheses of how volatiles may move between reservoirs or be sequestered, and of the large-scale effect of these volatiles on the Martian environment. The potential of these new hypotheses to refine our knowledge of fundamental Martian processes makes addressing them even more important than recognized in the current Planetary Science Decadal Survey. Some of these investigations are important because discoveries have shown that not all of the critical processes have been identified or quantified, and current or ongoing technological development presents options for investigating these processes or their records, potentially in situ, in the next decade. For example, despite a range of investigations of the appearance of the Martian residual caps, we do not know if either of the polar caps are undergoing net accumulation or erosion, or the composition of individual layers within the polar layered deposits (PLDs). Additionally, numerous recent observations of present-day activity and young landforms have led to debate about the ways in which Mars' volatile cycles influence the Martian climate and shape its surface. Conclusive identification of liquid water and its effects on the Martian surface would have grave implications for investigations under every MEPAG Goal; however, observations over the last decade of ongoing change have shown that some landforms that were thought to be relics of a different past climate are forming today with processes likely driven by seasonal CO_2 frost. Debates over liquid water highlight the importance of investigations of the Martian climate and volatile systems at all scales, from processes in the regolith to the planetary climate, and over timescales from diurnal variations to orbital cycles.

These discoveries place Martian ice and climate science at a tantalizing point. We have identified a variety of ice deposits and developed hypotheses for how they are shaped by the climate, but we have not yet read the history that they record. We have identified dynamic evolution of the surface by processes both predicted and unexpected, but cannot yet extrapolate their effects back in time with confidence. There has been a revolution in our understanding of these issues in the eight years since the current Decadal Survey was published, and future missions guided by new questions would test newly developed climate hypotheses and likely uncover even more important climate-related processes.

The effects of taking the next steps in these studies will be far-reaching. Characterizing the recent climate history of Mars with instruments specifically designed to test these new models would uncover the fundamental processes of the Amazonian period—over half of Mars' geologic history—and answer key components of the Decadal Survey objectives. Furthermore, it would provide a second terrestrial planet to compare with the Earth, strengthening our understanding of our own environment. This understanding would also impact studies of the outer solar system and exoplanets: Mars two major volatile ices, one that comprises the vast majority of its atmosphere, and their actions in its cold climate will help us understand how worlds that exist with only solid and gaseous phases at the surface evolve.

As one may expect, all of these recent discoveries have led to an increased focus in the Mars science community on investigations of the recent/present-day climate and ice reservoirs, reflected in recent meetings such as the 6th International Conference on Mars Polar Science & Exploration (September 2016) [Smith, I.B., et al., 2018a], Mars Workshop on Amazonian and Present Day Climate (June 2018) [Diniega & Smith, *submitted*], Late Mars Workshop (October 2018), and Keck workshops "Unlocking the Climate Record Stored within Mars' Polar Layered Deposits," I and II (August and November 2017) [Smith, I.B., et al., 2018b] and "MarsX: Mars Subsurface Exploration" (February 2018) and the upcoming 7th International Conference on Mars Polar Science & Exploration (January 2020). These meetings have been well attended, including many young scientists. Nearly 25% of attendees at these meetings are early career researchers and students, reinforcing how ice and climate investigations are seen as vital areas of investigation by the Mars scientists who will be the future of the field.

Finally, the research showcased in those and other conferences, and the accumulation of major recent discoveries, led to an evaluation of the 2015 MEPAG goals document and an update. The 2018 MEPAG Goals Document was updated to reflect modern questions and incorporate changes that focused on polar science, active processes, and the ongoing evolution of Martian volatiles and climate [MEPAG, 2018]. Following that update, the ICE-SAG was formed so as to identify what might be done in the coming decade (2023–2032) to achieve compelling Mars ice and climate science results in furtherance of these revised goals, and to provide guidance for enabling future Mars missions that could address these objectives.

1.2 Goal and Scope of this SAG

As explained above, the focus of ICE-SAG is on high-priority Mars climate and ice science, as it relates to determining Mars recent or Amazonian history. In particular, we focus on the

science questions that have been prompted or refined by recent new science discoveries. Thus, we recognize that studies of the Martian climate and ice reservoirs have been ongoing and advancing for as long as Mars has been studied through a telescope, but when describing the state of Mars ice and climate science and presenting the context of current high-priority questions, we focus on recent updates.

Furthermore, we focus on **science questions that require the acquisition of new data** -- either through ongoing or future missions, or through investment in laboratory, field, or modeling studies for improved interpretation of observational data. While other Martian geologic processes (such as volcanism) may have impacted Mars' recent climate and volatile distribution, it is less clear what data are needed to meaningfully advance our understanding of the Martian climate and ice history, and thus consideration of those types of processes were considered beyond the scope of the ICE-SAG charter and are not discussed in this report. This also led us to consider methane primarily in the context of ice detection investigations rather than as a separate climate-affecting volatile; we anticipate that ongoing missions (such as ESA's Trace Gas Orbiter (TGO)) will advance our general understanding of methane sources/sinks and processes.

Additionally, while existing observations have yielded the relevant recent key discoveries, addressing new questions generally requires new observations – either a completely new dataset or an improvement in resolution or coverage over an existing dataset. Furthermore, the current fleet of missions and instruments is aging. This prompted our chartered task to develop new mission concepts, and in particular to focus on whether there were **mission concepts that could achieve compelling Mars climate and ice science within NASA's New Frontiers cost-class (<$850M)**.

Finally, as will be discussed below, ICE-SAG was chartered to prioritize the mission concepts discussed. ICE-SAG did this by **prioritizing the science questions and measurements, and then focusing only on those mission concepts that addressed high-priority science questions/measurements**. As will be shown, to address the general question of Mars' recent climate history, there are many high-priority science areas that each address a key part of that history. It is too much to expect that a single mission concept can address all parts, and so instead we have a set of questions and needed measurements that are all high-priority, and a set of mission concepts that each address significant parts. To fully understand Mars recent climate history, several complementary missions would be needed. However, we emphasize that flying any one of the mission concepts described in this report (or other mission concepts that achieve the high-priority measurements outlined) would yield a meaningful advancement in our understanding of Mars recent climate, and would significantly add to our understanding of Mars as a system and of the climate and geologic history of terrestrial bodies and volatile processes within our Solar System. Thus, we ended up not further prioritizing between our mission concepts.

1.3 ICE-SAG Tasks and Structure

The ICE-SAG was led by Co-chairs Serina Diniega (JPL) and Than Putzig (PSI). The twenty additional members of the SAG, who are listed at the start of this report, were selected for their relevant expertise in various disciplines and study types (i.e., theoretical studies, analysis of observations, modeling, laboratory, and terrestrial field studies), and are from a range of institutions, career-levels, and demographics. To address missing expertise within the SAG, numerous subject matter experts were invited to speak to the ICE-SAG (Appendix B).

The ICE-SAG's first task was to identify the compelling science objectives that could be addressed in the next decade (2023–2032). Towards this aim, five subgroups identified open ice- and climate-relevant science questions within:

1. The climate record in the polar perennial ice (including the polar layered deposits),
2. Mars' thermal and energy budget (with a focus on global-scale questions),
3. deposition/preservation/evolution of perennial subsurface ice, at all latitudes,
4. the role of volatiles in active surface change and surface-atmosphere exchange, and
5. the atmospheric state and cycles that drive material or energy flux.

In this work, ~200 Mars ice- and climate-related science questions were identified (Appendix C), with traceability to the recently updated MEPAG science Goals (Life, Climate, Geology). These subgroups also identified measurements needed to address these questions, both orbital- or ground-based.

This broad list of questions was organized into one framework, and high-priority science areas (within a subgroup and repeated between subgroups) identified. Consideration of priority also included consideration of feasibility of making the needed measurements within the next decade (i.e., technological maturity). This yielded five Priority Science Areas, whose measurements are traced to some proof-of-concept techniques for making these measurements (§3). Challenges in making the measurements were also identified to inform technology investments that would enable acquisition of a measurement or to bring a technique to a sufficient level of maturity (§5). Challenges in interpreting a measurement were also identified to inform laboratory work, numerical modeling, and field studies that would enable or enhance science return of needed measurements (§6).

From the Priority Science Areas, mission approaches were developed that could address the compelling science objectives and make the required measurements (§4). As chartered, this group considered a range of mission types (i.e., orbiters, landers, drillers, rovers, networks), and different mission classes (i.e., small spacecraft, or NASA-cost classes of Discovery: ≤\$500M, New Frontiers: ≤\$850M, Large/Strategic: >\$1B). To better develop these concepts, a brief (9 hrs total) JPL Team X architecture study was commissioned to explore five mission concepts and the Mars Program Office Advanced Formulation Engineering group briefly explored an additional mission concept; a summary of their results is included as *Supplemental Materials*[3]. These high-level engineering-focused concept designs were intended to identify and explore the main technological challenges of the range of mission concepts defined by ICE-SAG and to explore some key high-level architecture trades. The engineering studies also helped identify the mission (cost) class a mission concept would likely fit within, although we emphasize that the resultant design and estimates are still very preliminary. Similarities between a particular ICE-SAG mission concept and the concepts used in these studies does not reflect prioritization of that concept, as the studies were designed to scope the range of possibilities being discussed.

Most of the ICE-SAG focus was placed on the concepts thought to fit within the NASA New Frontiers-class as (1) these presented mission concept options that generally could be "scaled" up or down with added or descoped science objectives to generate mission concepts fitting other classes, and (2) the SAG had been asked to prioritize the New Frontiers and Flagship class missions for possible costing and technical evaluation (CATE) by NASA in preparation for consideration in the next Planetary Decadal Survey for 2023–2032 (Appendix A).

[3] Posted as a separate document, with this final report, at https://mepag.jpl.nasa.gov/reports.cfm?expand=topical.

We note that the mission concepts described in this report are considered high priority in the sense that these concepts flow from and would address ice- and climate-science questions within our identified high-priority areas of scientific investigation (§3). However, we do not assign a prioritized ranking of the mission concepts because discussions within ICE-SAG did not yield a clear consensus on the relative importance of the sets of measurements or the feasibility of carrying them out, nor are the concepts sufficiently developed to allow a proper assessment of priority. (Additionally, after ICE-SAG had defined its mission concepts but before ICE-SAG completed its discussions and report, a NASA Research Announcement to select mission concept studies for technical development and costing evaluation came out, and we did not want to unduly influence that competition.) Furthermore, we emphasize that while the mission concepts described in this report were considered by ICE-SAG as reasonable and feasible ways to address key science gaps (see Tables 7.1 and 7.2 in §7), they are offered as *examples* of feasible ways to address these gaps; different approaches for addressing these gaps are likely possible and will evolve with regards to feasibility as technology development continues.

The ICE-SAG work was completed primarily via telecons and email exchanges, during the period October 15, 2018 through mid-April 2019. One face-to-face meeting was held January 17–18, 2019 at the PSI Headquarters in Tucson, AZ. A progress report was delivered to the MEPAG Executive Committee in mid-December 2018 and then to the MEPAG community during a MEPAG virtual meeting (VM4: February 25, 2019). In addition to this report, the ICE-SAG results were presented via poster at the 2019 Lunar and Planetary Science Conference [Putzig et al., 2019], a pre-print version of the final report was publically released May 28, 2019, and a final presentation was given during the next MEPAG virtual meeting (VM5: June 6, 2019). The full ICE-SAG schedule is shown in Figure 1.1.

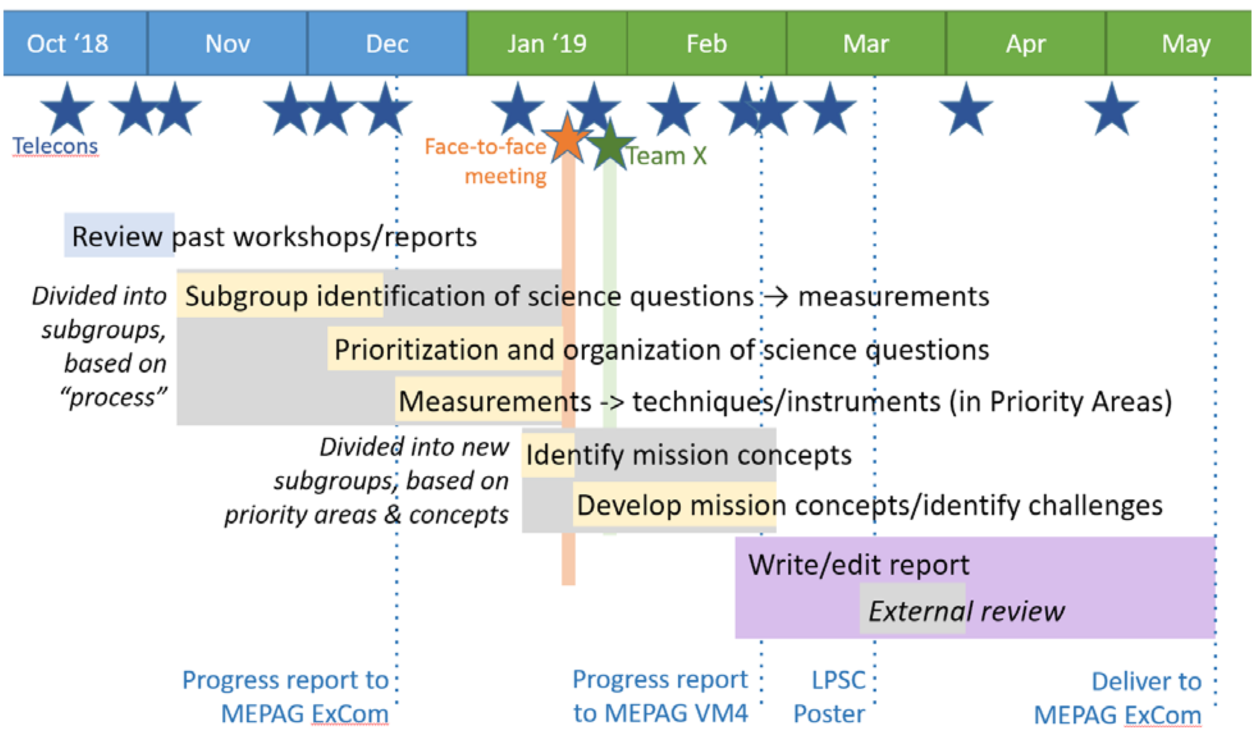


Figure 1.1. *The ICE-SAG work and report schedule, through delivery of the Pre-print report at the end of May. (Updates to the final report, from the Pre-print, are minor typo corrections, fixing of links, and addition of Appendix C.)*

2 Current State of Knowledge

In this Section, we give a brief overview of the current state of knowledge regarding the different types of recent climate records that have been identified and characterized on Mars. We also discuss present-day processes and environmental conditions that yield insight about previous processes and environmental conditions that formed or modified these records. *Our aim is to set context for identifying current high-priority open questions, and so we focus on recent discoveries and results as these provide the framework for new or refined science questions.*

The best records of recent Martian climate history are thought to be contained within reservoirs of water ice and carbon-dioxide ice, with this history reflected in its geographic distribution, depth, thickness, and internal structure and composition. In particular, the widespread and quasi-periodic sequences of water-ice layers observed within the north polar layered deposits (NPLD) are thought to be a decipherable record representing global-scale recent climate, likely analogous to layers within terrestrial ice cores [e.g., Hvidberg et al., 2012]. Terrestrial ice cores from the polar ice sheets are the best records of Earth's climate shifts over hundreds of thousands of years (Greenland) to millions of years (Antarctica). In the terrestrial case, ice cores may have annual resolution corresponding to seasonal variations in climate parameters (dust, stable isotopes, etc.), and deep ice cores (e.g., from Antarctica) reveal climate variations related to orbital forcing (Milankovitch cycles in obliquity (41 kyr) and precession (23 kyr) [Hinnov, 2013; Jouzel et al., 2007] (Figure 2.1); obtaining similar information from Martian ice layers would revolutionize our understanding of the Martian climate cycles.

Additionally, the net accumulation of Martian water ice is hypothesized to shift between the poles and mid-latitudes due to shifts in the planet's obliquity, and thus mid-latitude ice deposits may reflect accumulation during a different, past climate epoch [e.g., Jakosky & Carr, 1985; Forget et al., 2006; Head et al., 2003; Mischna et al., 2003; Mustard et al., 2001]. Understanding the preservation of those subsurface ice reservoirs into the present provides information about past and present-day processes and environmental conditions.

In the present climate, and presumably through the Amazonian, CO_2 is the dominant atmospheric volatile. Twice each year, ~25% of the CO_2 in the Martian atmosphere freezes out in a seasonal cap across the higher latitudes of the winter hemisphere [Genova et al., 2016; Paige and Wood; 1992; Wood & Paige, 1992], and the southern pole contains a ~1-km-thick deposit of carbon-dioxide ice thought to have accumulated in at least three recent periods of atmospheric collapse [Bierson et al., 2016; Manning et al., 2019].

Both water and CO_2 move around Mars due to seasonal forcing. These forcings will have interannual variations. Additionally, Martian seasons are affected by the planet's large orbital eccentricity (perihelion at 1.36 AU obtains 40% more solar energy than aphelion at 1.64 AU). The planetary tilt (obliquity), currently at 25° and similar to Earth's, changes and wobbles over time in obliquity cycles with periods of ~120, 60, and 50 kyr [Laskar et al., 2004]. As increases in the Martian obliquity moves the latitude of ice deposition from the polar regions to lower latitudes [Jakosky & Carr, 1995], and vice versa, understanding Mars' climate history thus requires investigating these ice reservoirs.

To 'decode' the record within these reservoirs, and to understand their formation, evolution, and stability, quantification of volatile and dust fluxes within the atmosphere and between the atmosphere and the surface and subsurface is needed. Determining how these fluxes are driven by present-day processes and environmental conditions requires measurement of those fluxes as well as characterization of current surface and atmospheric conditions, through diurnal and seasonal

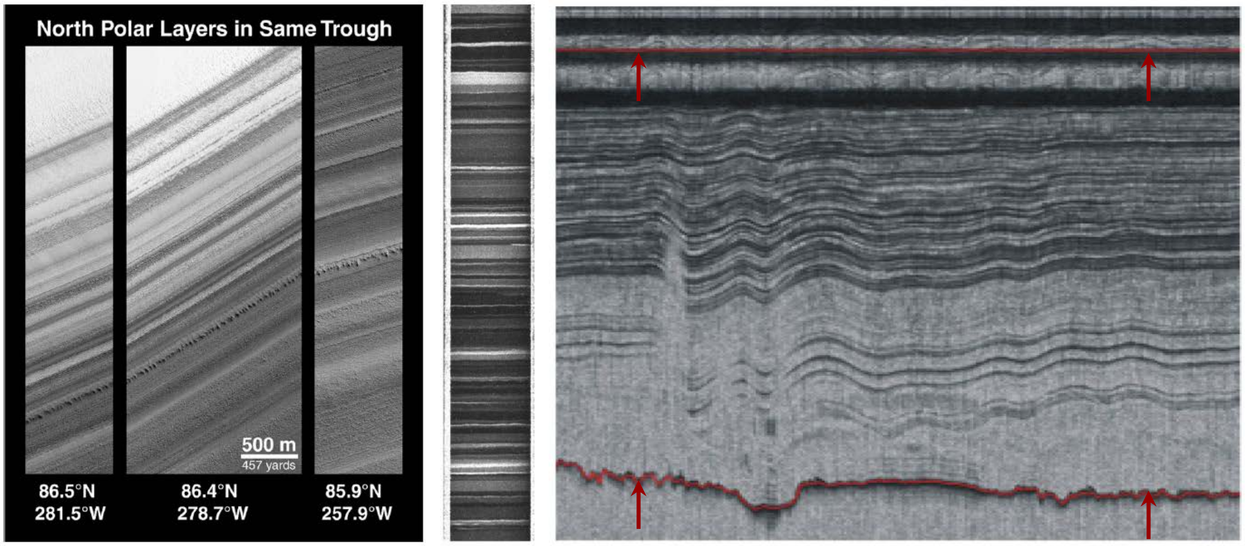


Figure 2.1. *Stratigraphy of polar caps on Mars and Earth.* Left: *(Mars) Visual images of the dark slopes reveal an extensive layering in a trough on the NPLD. More than 100 km separate the image locations (MGS MOC2-148, Malin Space Science Systems/NASA). The layering records climate changes on Mars thought to be modulated by orbital variation.* Center: *(Earth) Visible stratigraphy in a 0.55 m long section of the NorthGRIP ice core [Svensson et al., 2005]. Annual layer thickness is 1.5 cm, the depth is 1837 m, and ice originated during the last glacial maximum (20 kyr ago). The layering reflects snow storms with different dust content and indicate an annual cycle.* Right: *(Earth) Radio echo sounding profile from North Greenland [CReSIS, 2016]. The red lines (at arrows) indicate the surface and the bedrock. The section is 150 km long with an ice thickness of appr. 2.6 km. Internal layers are isochrones, and their elevation reflect the history of flow and accumulation. Increased geothermal heat flow may lead to basal melting (indicated by undulations of the layers without relation to basal topography). The internal layers can be traced over most of Greenland and reflect variations in impurity content (dust, chemical impurities). The darker layers in the top half correspond to ice younger than 14.5 kyr, corresponding to the present interglacial period. The layers in the bottom half correspond to abrupt climate transitions during the last glacial period. Similar radar profiles are available for Mars (e.g., Fig. 2.2).*

cycles. It also will require determining the level and type of connections between present-day activities and layer-formation and evolution processes, and the range of timescales that are likely involved in forming the layers within the full ice records (from seasonal and annual processes and cycles to the multi-year, possibly hundreds or more, record that may be within a layer); this work will heavily involve observations and modeling of present-day conditions and processes, modeling of processes at work over longer time periods or under different climatic conditions, and detailed observations of the layers themselves.

Finally, some landforms have been hypothesized to be connected to particular environmental conditions, often including volatiles in a specific state (i.e., frozen, liquid, or vapor) — recent examples that have been a focus of many recent studies are Recurrent Slope Lineae and gullies. If a robust connection can be identified between specific processes or environmental drivers and a given landform, then that landform can serve as a proxy record of the climate at the time of its formation or evolution. Thus, such relict or actively forming features are of importance for climate studies.

In this section, we discuss the current state of knowledge about all of the areas described above. As explained in §1.2, we note that this section is not meant to provide full review of the literature; we focus on recent discoveries and related shifts in our understanding of Martian processes and climate history. In addition to discussing geology and climate implications that come from an improved understanding of Mars' recent climate, we discuss implications for astrobiological and human exploration investigations. As will be discussed in this section, ICE-SAG finds the following:

ICE-SAG FINDING 1. Recent discoveries and studies of Mars' ice reservoirs have significantly changed our views of ice occurrence on Mars, its role in driving surface and subsurface processes, its implications for astrobiological studies, and its potential for in situ resource utilization. These advancements enable a new definition of investigations that would make key measurements to provide a new understanding of these records of the recent climate of Mars.

2.1 Recent Climate Record: Ice Reservoirs

2.1.1 Residual Caps and Polar Layered Deposits (PLD)

The Polar Layered Deposits (PLDs) extend more than 1000 km across at each pole and are the largest known ice reservoirs on Mars. Similar to terrestrial polar ice sheets, their stratigraphy has long been thought to record Martian climate states and shifts (Fig. 2.1), likely driven by orbital forcing [e.g., Hvidberg et al., 2012; Laskar et al., 2002; Milkovich & Head, 2005; Murray et al., 1972; Thomas et al., 1992]. The stratigraphy of the PLDs formed due to variations in the deposition of ice and dust and is thought to reflect past climate changes on Mars (Fig. 2.2). Dust is a key component of Martian climate and its transport and deposition at the poles is controlled by global scale atmospheric conditions. Dust can also drive ice condensation, with the particles acting as nucleation sites [Gooding, 1986; Santiago-Materese, et al., 2018]. Ice deposition reflects local climate conditions controlled by insolation as well as global redistribution of water and carbon dioxide on million year timescales. Thus, the archive of past climate contained in the PLD stratigraphy informs climate conditions over time at the poles and globally.

The surface ages, composition, structure, and morphologies (at large and small-scale) of the NPLD and SPLD differ considerably so these deposits likely record climate from different parts of the Amazonian. A small crater population on the NPLD is consistent with ongoing ice accumulation over the past 20 kyr [Banks et al., 2010] or resurfacing within the last 1 kyr [Landis et al., 2016]. The SPLD crater record indicates a surface age of 30-100 Myr [Koutnik et al., 2002]. The ages of deeper layers are not known with certainty, however, simulations of past climate [e.g. Levrard et al., 2007] indicate that the NPLD may have started accumulating ~4 Myr ago and this scenario is consistent with stratigraphic comparisons [Hvidberg et al., 2015; Becerra et al., 2017]. (Although some have debated correlating stratigraphy and orbital shifts [Perron & Huybers, 2009], more recent work that carefully considers what may differentiate layers has confirmed such correlations [Sori et al., 2014].) The large-scale layering of the PLD has been illuminated through visible imaging of exposures in troughs and scarps, and radar sounding of the interior, which yields coarse stratigraphy and bulk composition. Radar and gravity data show both PLDs are composed primarily of water ice with non-ice materials making up a few percent of the total mass [Grima et al., 2009; Plaut et al., 2007; Wieczorek, 2008; Zuber et al., 2007].

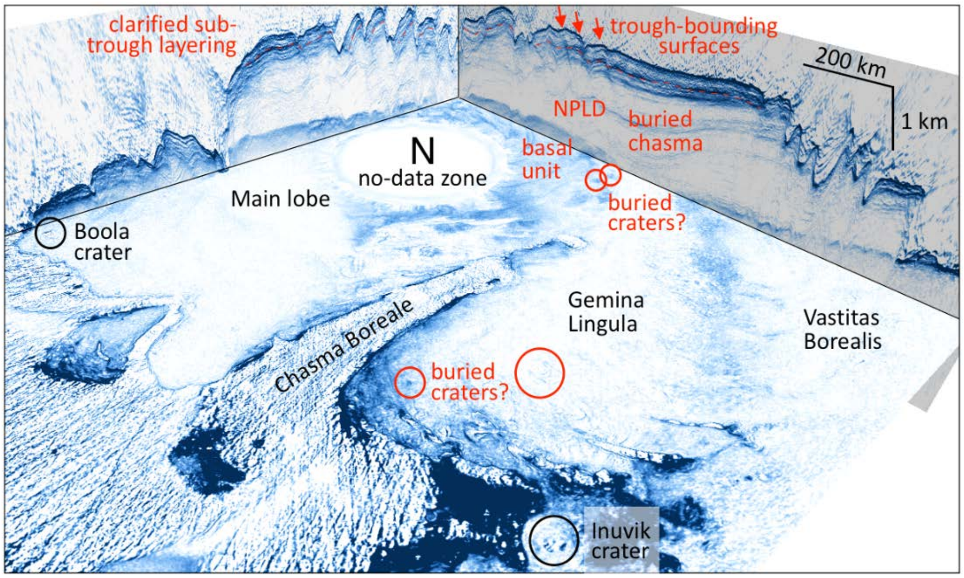


Figure 2.2. *Radar sounding has revealed interior layering and apparent buried craters in both polar regions of Mars. Here, we see a perspective view into a 3-D radar volume of SHARAD data, showing radar-return power (blue high, white low) from previously known (black) and buried (red) features within the north polar cap. The no-data zone is due to MRO's orbit inclination. Depth conversion assumes pure water ice and scale is approximate (varies in this perspective), with vertical exaggeration of 136:1. From Putzig et al. [2018].*

The uppermost layer of the PLD of each hemisphere is a residual ice cap (i.e., the North Polar Residual Cap (NPRC) and South Polar Residual Cap (SPRC)). The NPRC is the dominant source and sink of atmospheric water vapor for the entire planet [Smith, M.D., 2008]. Figure 2.3 shows the NPRC, which is one of the flattest, most monotonous regions on Mars [Aharonson et al., 2001], with a gentle, hummocky texture covering hundreds of kilometers in every direction. The NPRC is composed of large-grained and dust-free water ice [Kieffer, 1990; Langevin et al., 2005], with finer-grained water frost present during spring [Brown et al., 2016], and is nearly contiguous with the NPLD in extent. Conversely, the SPRC is high-albedo CO_2 ice with exotic erosional morphologies [Thomas et al., 2000] over water ice [Titus et al., 2003] that covers only a small portion of the underlying SPLD and is geologically distinct from the SPLD [Thomas et al., 2000]. Sequestered CO_2 deposits beneath the SPRC, which exceed the mass of the present CO_2 atmosphere, have been detected by the Shallow Radar sounder (SHARAD) on the Mars Reconnaissance Orbiter (MRO) under the SPRC [Bierson et al., 2016; Phillips et al., 2011].

Modern observations have shown that accumulation within the PLDs have not been uniform, either horizontally or vertically. Outcrop imaging at CTX resolution (~ 6 m) is nearly complete, and HiRISE coverage (sub-meter) exists in many locations (examples shown in Figures 2.1, 2.3). Between outcrops, orbital radar stratigraphy from SHARAD at ~10 m vertical resolution (Fig. 2.2) and the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument on the Mars Express spacecraft at ~100 m vertical resolution also exists. Together, SHARAD and MARSIS have illuminated much of the 3-D internal structure of the polar ice deposits and can provide insights into their bulk composition and density, potentially revealing dust contents. But a gap remains within the upper 1–10 meters which are unresolvable by both instruments; this depth range is critical for understanding how volatiles transfer through or interact with regolith in the present climate, as well as for enabling future access to near-surface ice reservoirs for scientific study or ISRU interests. HiRISE has been able to provide information on PLD beds less than a meter thick, but relating visible data to internal structure is not straightforward, nor is it easy to

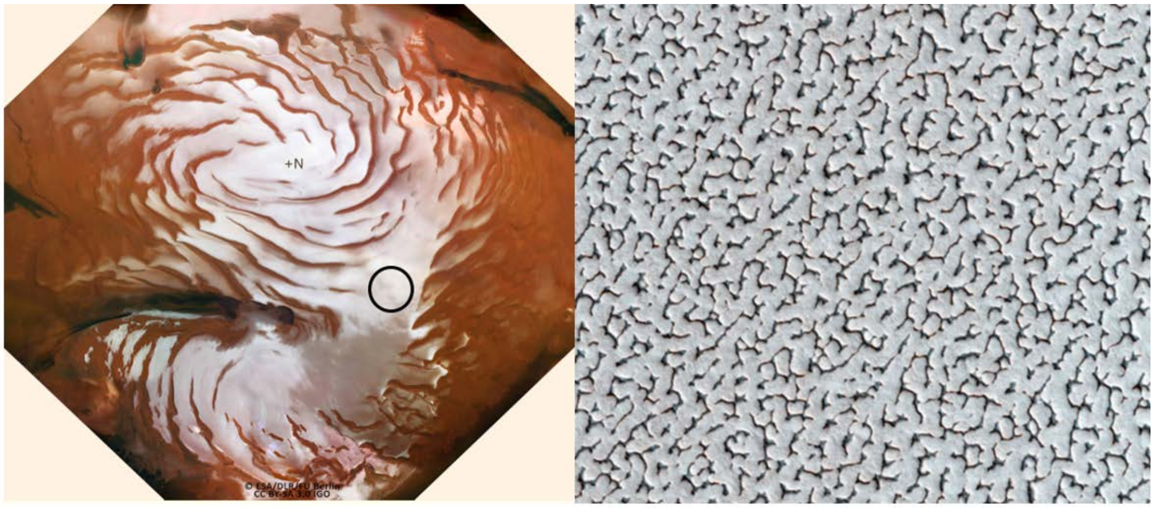


Figure 2.3. *Images of the NPRC, showing the terrain in this region.* Left: *HRSC mosaic of the NPRC, with pole marked and a circular area with diameter ~63 km (i.e., ~MER-type landing ellipse of unknown orientation) included for scale.* Right: *An example of the typical NPRC surface, with <1 m tall [Herkenhoff et al., 2002], ~20 m-wavelength gently rolling hummocks (i.e.., ~20 m is the distance between the dark patches) [https://www.jpl.nasa.gov/spaceimages/details.php?id=PIA18111].*

correlate outcrops observed at different locations around the PLDs. Regular periodicities in marker bed and layer sets have been studied in both PLDs and hypothesized to connect to specific orbital cycles [e.g., Becerra et al., 2016; 2017; Fishbaugh & Hvidberg, 2006; Fishbaugh et al., 2010; Herkenhoff et al., 2007; Hvidberg et al., 2012; Putzig et al., 2009; Smith et al., 2015]. However, it is not known if the present state of either residual ice cap is that of net accumulation or net erosion. Similarly, it is not understood how the current annual rates of deposition and sublimation may relate to the layer sequence, nor is the relationship of deposited layers to climate cycles understood. Thus, open questions include the current mass balances, amounts of seasonal deposition/ablation, dynamics of short-term and long-term exchanges with lower latitudes, compositional variations in shallow stratigraphy, and links between stratigraphy and orbital forcing.

2.1.2 Sub-PLD ice deposits

Beneath the PLDs are geological units that appear to record the onset of growth of the polar plateaus and PLDs, and that may be significant CO_2 or water ice reservoirs. While these units are less well characterized than the PLDs due to their location deep beneath the polar ice and limited surface exposures, much progress has been made through analysis of their radar properties and image and topographic analyses of outcrops.

With the exception of Gemina Lingula (labeled in Fig. 2.2), much of the NPLD overlies the north polar "Basal Unit" (BU) [Tanaka et al., 2008]. This layer appears relatively dark and coarsely layered where it is exposed, but density estimates suggest it is still ice-rich (e.g., ~27-55% ice from gravity [Ojha et al., 2019]) and likely is a significant Martian water ice reservoir. The BU appears to overlie materials similar to the rocky Vastitas Borealis interior unit that extends across the northern plains and is thought to be formed of Hesperian-aged fluvial and lacustrine sediments [Tanaka & Fortezzo, 2012]. MARSIS radar signals are able to penetrate through the NPLD and BU, showing basal reflectors interpreted to be the contact with materials contiguous with the

Vastitas Borealis interior unit [Picardi et al., 2005; Selvans et al., 2010]. SHARAD radar data generally show reflections from the top of the basal unit (but not from the base), and have revealed the surface topography of the basal unit, showing that it exhibited a strong control on the present layering and topography of the NPLD [Brothers et al., 2015].

The BU outcrops mostly at scarps within Chasma Boreale and Olympia Cavi and is thought to be the source of sand for the current circumpolar dune fields [Byrne and Murray, 2002; Fishbaugh and Head, 2005]. Collectively, current observations support the view that the cavi unit and NPLD form a continuous sequence, and reduction in sand supply and orbital forcing caused the transition to modern deposition of more pure deposits of water ice [Herkenhoff et al., 2007; Brothers et al., 2018; Nerozzi and Holt, 2018].

At the South Pole, layering is discontinuous and the transition from the SPLD to lower units are less clearly defined [Plaut et al., 2007; Seu et al., 2007; Whitten and Campbell, 2018]. Planum Australe rests on the heavily cratered southern highlands and partially covers the Prometheus impact basin. MARSIS data show that the surface is irregular at the base of Planum Australe and contains several large depressions [Plaut et al., 2007]. The Hesperian-aged Dorsa Argentea Formation, a possible sedimentary deposit from a formerly greater extent of a south polar ice sheet, forms plains adjacent to Planum Australe. Geological mapping indicates that the Dorsa Argentea Formation extends beneath the SPLD [Tanaka & Kolb, 2001]. MARSIS radar observations over most of the SPLD show reflections interpreted to be the interface between the SPLD and underlying lithic substrate [Plaut et al., 2007], however, the exact nature of the basal substrate is unclear due to an absence of exposed outcrops.

Recently, radar observations were interpreted as evidence that subsurface liquid water may exist at the base of the SPLD: MARSIS observations of unusually high-powered radar reflectors in a localized area beneath the SPLD [Orosei et al., 2018] point to a basal material with a high permittivity, consistent with briny water. However, because of the low temperatures of this region, modeling indicates that a greatly enhanced geothermal flux (possibly from a recent shallow magma chamber) is required for basal melting to occur regardless of the salt content of the water [Sori and Bramson, 2019], and debate about this interpretation continues.

2.1.3 Non-polar subsurface ice deposits

The shallow subsurface of Mars has long been understood to be a major volatile reservoir, particularly in terms of storing large volumes of water ice [Smoluchowski, 1968]. Due to perennially cold Martian temperatures and low atmospheric pressure, Leighton and Murray [1966] first postulated that atmospheric water vapor would diffuse into the regolith pore space and be cold-trapped as subsurface ice at depths of centimeters to decimeters poleward of ~50° in both hemispheres. This theoretical prediction was supported qualitatively by extensive geomorphological indicators of subsurface ice [e.g., Carr, 1996]. Over a ~30 year period Leighton and Murray's approach was expanded and refined to make detailed predictions of the global geographic distribution and burial depth of shallow ice in the current climate [Bandfield et al., 2007; Fanale et al., 1986; Farmer & Doms, 1979; Mellon & Jakosky, 1993; Mellon et al., 2004; Paige, 1992; Schorghofer & Aharonson, 2005; Sizemore & Mellon, 2006; Sizemore et al., 2009; Zent et al., 1986] and under past conditions driven by orbital forcing [Mellon & Jakosky 1995; Chamberlain & Boyton, 2007; Steele et al., 2017; Zent 2008].

Broadly, these predictions were confirmed by the *Mars Odyssey* Neutron and Gamma-Ray Spectrometers (MONS/GRS), which detected ice at burial depths and geographic locations within the high latitudes strikingly consistent with theoretical predictions [Boynton et al., 2002; Mellon et al., 2004; Mellon et al., 2009; Prettyman et al., 2004; Sizemore et al., 2010] and by the Phoenix lander which directly observed very near-surface ice [Smith, et al., 2009]. However, beginning in the early 2000s, high-resolution morphological analysis, together with MONS data, challenged the common theoretical assumption that the volume fraction of shallow subsurface ice was small enough to be contained in the pore space of the regolith and the assumption that vapor diffusion was the primary delivery mechanism for extant ice in the subsurface [e. g., Feldman et al., 2008; 2011; Head et al., 2003; Prettyman et al., 2004]. Specifically, analysis of MONS data indicated that materials in the top meter of the regolith consisted of >75 vol. % ice over large portions of the northern hemisphere poleward 50° N. These "Latitude Dependent Mantles" were first described in 2001 [Mustard et al., 2001] and were interpreted as airfall dust deposits with an ice component [Kreslavsky and Head, 2002; Milliken and Mustard, 2003]. This characterization rapidly shifted to a paradigm in which the mantles were commonly characterized as the remnant left by sublimed glacial deposits, with an assumption of ice having been the volumetrically dominant component when originally deposited [Head et al., 2003; Kreslavsky et al., 2006; Schon et al., 2009].

The arrival of MRO at Mars in 2006 ushered in an era of ever-increasing evidence for extended deposits of nearly-pure water ice in the upper few to ~100 meters of the subsurface. The HiRISE camera revealed fine layering in mantle deposits [Schon et al., 2009; Searls et al., 2008], clean ice exposed by fresh impacts [Byrne et al., 2009; Dundas & Byrne, 2010; Dundas et al., 2014], thermokarst terrains suggestive of thick ice deposits [Viola et al., 2015; Dundas et al., 2015] and instances of exposed massive ice in mantle scarps [Dundas et al., 2018]. In addition, though still debated, a variety of additional landforms are suspected to be indicative of past (and potentially present) ground ice. Forms of polygons are thought to arise via thermal contraction cracking in ground ice [e.g., Levy et al., 2009; Mellon et al., 2008; 2009]. The thermokarstic terrains, which include features such as scalloped depressions (Fig. 3.6) and expanded craters, are thought to indicate ice loss via sublimation [e.g., Morgenstern et al., 2007; Lefort et al., 2009; 2010; Viola et al., 2015; Zanetti et al., 2010] or melting [e.g., Costard & Kargel, 1995; Soare et al., 2008]. Such collapse likely indicates that there was a high ice content in the subsurface, and the lack of any collapse between these features may indicate a continued presence of ice in portions of the landscape. Candidate pingos [e.g., Burr et al., 2009; Dundas & McEwen, 2010; Soare et al., 2014] could indicate local ground freezing conditions, though other interpretations have been offered [e.g., Jaeger et al., 2007; Dundas et al., 2015]. Lobate features [e.g., Gallagher & Balme, 2011] have been suggested to indicate creep or freeze-thaw cycles.

Radar detections consistent with clean subsurface ice have been seen in mid-latitude locations where ice is not thermally stable at present. The preservation of such ice may be difficult to reconcile with theory, depending on assumptions made about the recent climate and atmospheric water content (§2.2.1) [Schorghofer & Forget, 2012], and the presence of a growing, insulating lag deposit may help explain the preservation of ice at these latitudes [Bramson et al., 2017]. Contemporaneously, SHARAD provided evidence that mid-latitude lobate debris aprons are essentially debris-covered glaciers consisting of nearly-pure ice [Holt et al., 2008; Plaut et al., 2009]. Additionally, SHARAD has provided evidence that large regions of Arcadia and Utopia Planitiae contain extensive ice-rich reservoirs in the near subsurface [Bramson et al., 2015; Stuurman et al., 2016]. However, the concentration of the ice within these deposits remains unclear [Campbell and Morgan, 2018]. Collectively, the recent data now allow a mapping of likely indicators of ice all across the mid-latitudes (Fig. 2.4) that will inform planning for future missions, including those involving human exploration wherein the ice can serve as an in situ resource (§3.7).

Despite growing evidence for massive ice deposits in the mid and high latitudes, there are persistent uncertainties in constraining the ice and lithic fractions of the upper 1–100 m and in linking these deposits to past climate cycles. Acquisition of new SHARAD data has challenged the interpretations that extended ice deposits in Arcadia and Utopia are nearly pure throughout depths of 10s to 100s of meters; new analyses suggest a potentially significant lithic content [Campbell & Morgan, 2018; Morgan et al., 2019]. The Phoenix lander provided a ground-truth observation of ground ice at a single location at 68°N and at depth of ~centimeters; however, most ice exposed by trenching at the landing site appeared to be pore filling (~50 vol. % ice, ~50 vol. % lithics), with small patches of nearly-pure "excess ice" exposed at some locations [Mellon et al., 2009]. Recent re-analysis of MONS data is consistent with stratigraphy caused by varying ice/lithic fractions in the uppermost 50 cm [Pathare et al., 2018]. Hence, while the existence of ice contents greater than regolith pore space is well-established, the thickness, spatial distribution, and origins of such ice are not presently understood.

Although shallow subsurface ice is not expected to be stable at low latitudes based on theoretical considerations, evidence has been proposed for the existence of past/present localized deposits. Radar sounder and neutron data exhibit evidence for ice deposits within the equatorial Medusae Fossae Formation [Watters et al., 2007; Campbell and Morgan, 2018; Wilson et al., 2018]). Glacial features, both preserved (at high altitudes) [Head et al., 2005] and inferred from their apparent interaction with volcanics [Hauber et al., 2008], have been identified within the Martian tropics. Likewise, rootless cones indicate that ground ice may have existed near the equator in geologically recent times [Lanagan et al., 2001]. Reactivation of deep-rooted faults, due to recent impacts or other tectonic processes, offer an additional setting for ice deposits [Etiope & Oehler, 2019].

Motivated by the observational data, theoretical studies in the MRO era have probed both the delivery and preservation of mid-latitude ice. Climate modeling combined with morphological analyses have established that precipitation and glaciation likely occurred in broad mid-latitude regions late in the Amazonian [e.g., Mischna et al., 2003; Forget et al., 2006; Madeleine, et al., 2009]. Simulations of the preservation of glacial ice against sublimation have shown that it is difficult [Schorghofer & Forget, 2012] but not impossible [Bramson et al., 2017] to retain massive ice deposits at these latitudes on the 10s of millions of years

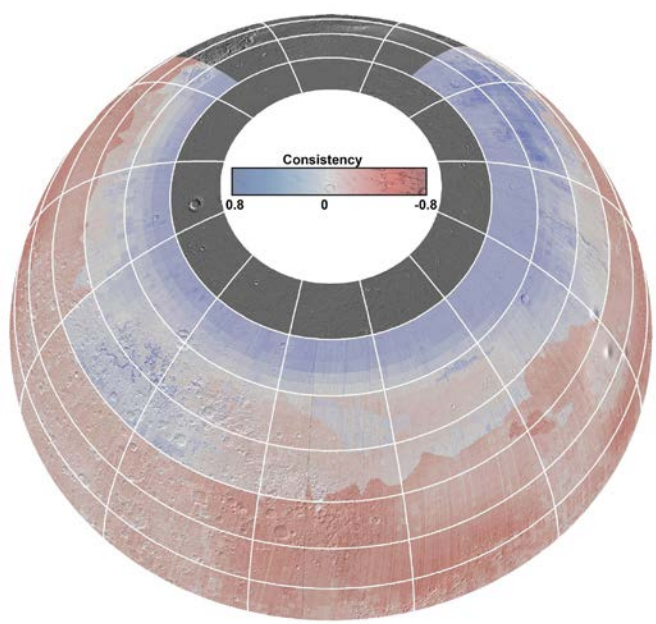


Figure 2.4. *Preliminary map of multi-dataset consistency with the presence of near-surface ice in the northern hemisphere of Mars (0 to 60°N, centered at 75°E) from Morgan et al. [2019]. Observations from radar, thermal and neutron spectrometers, a laser altimeter, and imagers (geomorphology) are considered together in producing this map, which aims to locate ice as a resource for future human exploration missions. Values of +1 and -1 indicate 100% consistency and 100% inconsistency of considered datasets as indicators of buried water ice.*

timescales likely required [Viola et al., 2015], depending on assumptions about past climate. At the same time, modeling of the occurrence of thin liquid films in the shallow subsurface has suggested that frost heave and the formation of ice lenses may have been common in the past 1 Ma (and the more distant past), contributing to stratigraphy in the uppermost meter [Sizemore et al., 2015] and potentially aiding preservation of deeper ice. However, atmospheric boundary conditions are weakly constrained over much of this complex history (§2.2, §2.3), and it is unknown what portion of existing ice is in equilibrium with current climate conditions.

Currently, mid-latitude ice can only be detected directly in cases where we can obtain high-resolution imaging of new impacts that expose and excavate into the ice [Dundas et al., 2014]. However, these impacts occur infrequently, are only detectable in dusty areas [Daubar et al., 2013], and are too small to excavate deeper than ~1 m. This greatly limits their utilization in systematically constraining the spatial distribution of ice. Also, because of the shallow depths probed by these craters and the limitations of the current instrumentation at Mars, we are therefore unable to directly detect ice in the depth range of ~1–10s of meters, which includes the depths with the most uncertainty in ice content heterogeneities as well as those that have been in this dynamic exchange with the atmospheric and climatic conditions. Neutron spectrometer data and diurnal thermal waves do not probe that depth range, and SHARAD cannot resolve features within that zone. Outcrops are few and are subject to surface/atmospheric exchange, so only very recent and inherently unstable (i.e., rapidly sublimating) exposures have directly revealed ice in the middle latitudes [e.g., Byrne et al., 2009; Dundas et al., 2018], and no landforms or surface activity have yet been conclusively tied to significant present-day ice at those depths.

In summary, the current theoretical understanding of non-polar ground ice paints a picture of complex stratigraphy on multiple length scales, and questions remain about the past and present stability of existing ice. As a result, there are major outstanding questions about the age, concentration, layering, and chemistry of the existing ice, the current fluxes of water vapor between the ice and the atmosphere, current dust deposition rates, and how volatile and non-volatile material fluxes are controlled by local weather conditions and soil properties.

2.2 Volatile Exchange with other Reservoirs & their Relation to the Climate Record

2.2.1 Atmospheric volatile history

Volatiles moving between and within the ice reservoirs are transported via the atmosphere, and can be modified through processes such as cloud formation. The Martian atmosphere is <1% the pressure of that of Earth, with a scale height of ~11 km (close to Earth's 8.5 km). The Mars atmosphere serves as a significant reservoir of volatiles (including CO_2, N_2, Ar, O_2, and CO) as well as dust. Over time, these atmospheric constituents can interact with each other, exchange with the near surface, and eventually be lost to space. The atmospheric pressure and composition also exhibit large seasonal changes, as up to 25% of the atmospheric CO_2 condenses at the winter pole, only to sublime back into gas during the spring and summer [Genova et al., 2016; Paige & Wood, 1992; Wood & Paige al., 1992]; isotopic fractionation can occur as volatiles condense onto the surface, as cloud particles, or as snow.

All atmospheric gases show enrichment in the heavier masses of their isotopic forms, consistent with loss of lighter gases through atmospheric escape processes over billions of years. This is evident in noble gases such as Ar, in CO_2 isotopic forms such as $^{13}CO_2$ and ^{18}OCO, in molecular nitrogen, and in atmospheric water vapor. The evidence for atmospheric loss through long-term escape processes has been provided by the *Mars Science Laboratory's* (*MSL*) in situ measurements with the Sample Analysis at Mars (SAM) instrument [Mahaffy et al., 2013; 2015], by *MAVEN's* measurements of the actual processes occurring at the edge of the upper atmosphere [Jakosky et al., 2018], by the meteoritic record [e.g., Greenwood et al., 2008; Leshin, 2000], and by Earth-based telescopic observations [e.g., Owen et al., 1988].

Isotopic fractionation in water occurs through either the vapor pressure effect between phases in equilibrium (which depends on temperature, partition functions, and includes equilibrium condensation) or through the kinetic effect (non-equilibrium, mass-dependent, diffusion limited processes such as evaporation, condensation, chemical reactions) [Criss, 1999]. Isotopic changes may be expressed as ratios such as D/H or in deltas such as δD where $\delta D = [(D/H)_{obs}/(D/H)_{SMOW} -1)]\times 1000$ ‰ and the reference value is the Earth's Standard Mean Ocean Water (SMOW). The current Mars atmosphere shows a range in δD of 4,000–7,000 ‰ which is equal to a D/H range of 5–8×SMOW [Villanueva et al., 2008]. If asteroids or comets deliver water to both Earth and Mars (as might be suggested by the fact that both carbonaceous chondrites and comets have δD relatively close to SMOW; Hallis, 2018), it is believed that the main primordial Martian water reservoir in the mantle should have a D/H ratio equal to 1×SMOW (Fig. 2.5). The hydrated crust is thought to have a D/H of 2–3×SMOW, while the near-surface water ice will have a higher D/H reflecting exchange with the atmosphere [Usui et al., 2015]. *MSL*'s Tunable Laser Spectrometer (TLS) instrument on SAM recently measured the D/H in water evolved from Hesperian clay [Mahaffy et al., 2015] as 3×SMOW to establish that ~3.2 Gya the planet had a global equivalent water layer of ~150 m compared to ~50 m estimated for today.

Isotopic measurements of water and other volatiles within the layers of the PLD would yield important information about Mars' climate history over millions of years (§2.1.1). Similar measurements are made using ice cores on Earth (e.g., Greenland Ice Sheet Project [Stuiver & Grootes, 2000]), where the annual temperature change and mean value is captured through the process in which polar transport of water vapor with continuous rainout produces temperature dependent changes in $\delta^{18}O$ or δD that establish the condensation/freezing environment at the time.

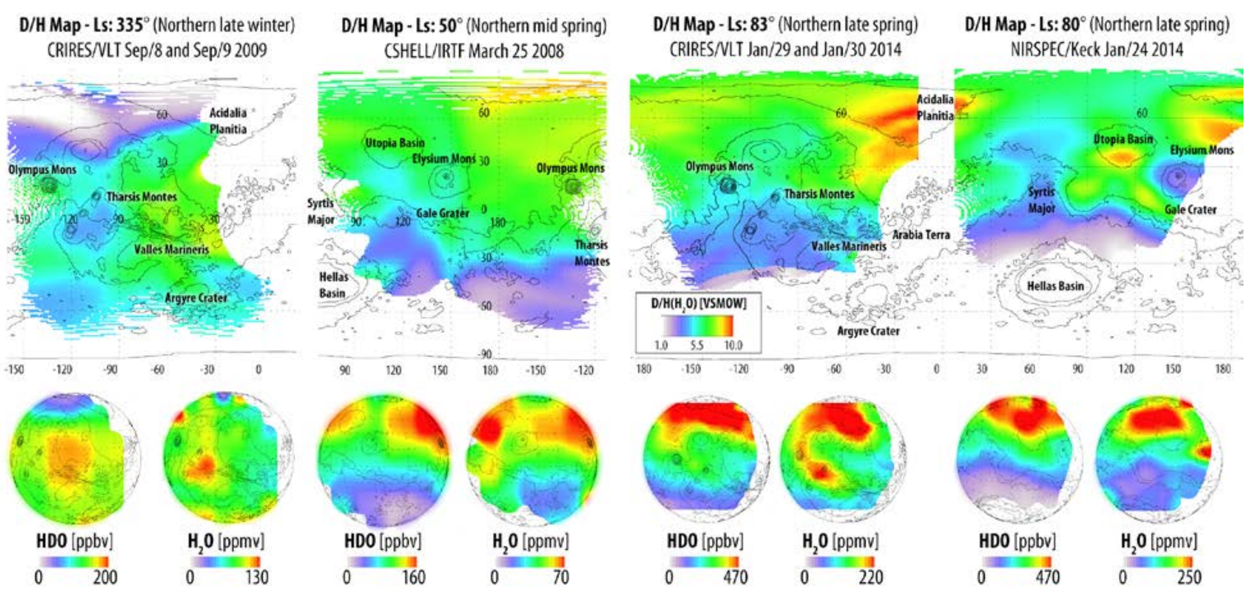


Figure 2.5. *Evidence of historical water reservoirs on Mars. Shown is a map of the Martian D/H ratio in water vapor recorded from ground telescopic observations over one Martian hemisphere [Villanueva et al., 2015] and now being recorded from orbit in greater detail by the ExoMars Trace Gas Orbiter (TGO) [Vandaele et al., 2018]. (Figure used with permission of G. Villanueva.)*

On Earth, $\delta^{18}O$ decreases by ~5‰ per ~5°C temperature drop, so that δD would be expected to drop ~50‰ for the same temperature drop.

Modeling of the isotopic evolution of the NPLD [Vos et al., 2019] indicates that the NPLD may have grown over the last few million years, and that during epochs of low and constant obliquity such as the last 400k years, the 50k year precession cycle should dominate the D/H variation. If the NPLD is growing, with a yearly accumulation being microns to millimeters-thick layer [Brown et al., 2016; Smith et al., 2016], this 50k cycle would be recorded over ~40 m depth. (However, whether the NPLD is currently growing remains an open question.)

2.2.2 H_2O exchange with the regolith and liquid water activity

In addition to holding subsurface water ice (§2.1.3), the Martian regolith harbors smaller quantities of H_2O in the form of adsorbed water, brine, pre-melted liquids at mineral-ice and ice-grain interfaces, or hydrous minerals (bound molecular H_2O). All four of these subsurface water reservoirs have the potential to exchange H_2O with the atmosphere, and these exchange processes are partially dependent on local relative humidity and temperature conditions [e.g., Chevrieret al., 2009; Farris et al., 2018; Fischer et al., 2014; Gough et al., 2011; 2016; Wang et al., 2009; 2013;]. For example, some hydrous minerals undergo changes in hydration state or crystallinity with exposure to changing humidity conditions [e.g., Vaniman et al., 2004; Xu et al., 2009] and undergo accompanying changes in volume upon transformation [e.g., Vaniman & Chipera, 2006]. Of particular interest are the processes of adsorption and salt deliquescence, which form liquids through development of thin H_2O films and grain-scale H_2O-bearing brines, respectively (Fig. 2.6). In addition, recent work suggests that brines can exist as liquids below the eutectic temperature for extended periods of time, and thus could be present in the shallow subsurface of surface of Mars [Primm & Stillman, 2019, and references therein]. Though the amounts of liquid water are likely too small to support life [e.g., Rivera-Valentin et al., 2018], all of these processes could play a significant role in triggering surface changes observed today (e.g., Recurring Slope Lineae, or RSL) [McEwen et al., 2011] as well as in the long-term regolith development and alteration of Martian rocks. Thin liquid films in permafrost may contribute to ice segregation and frost heave [Sizemore et al., 2015] and the preservation of biosignatures [Toner et al., 2014]. Thus, a better understanding of the extent and kinetics of liquid water activity as well as potential ongoing phase transformations in the shallow subsurface has broader significance as it may help elucidate active surface processes and the evolution of soil chemistry and physical properties over time (§6.2).

2.2.3 Methane

Another Martian volatile that has been a focus of recent high-profile observational studies is methane. Reports of spikes, plumes, and seasonal oscillations in atmospheric concentration of methane have prompted hypotheses of Martian methane origins from both abiotic processes (summarized in Oehler & Etiope [2017]) and potential biotic sources (methanogenic microorganisms) [e.g., Yung et al., 2018.]. In addition, it has been suggested that profuse methane releases may have contributed significantly to an early Mars greenhouse effect [Oehler & Allen, 2010], as has been suggested for the Earth [e.g., Kvenvolden & Rogers, 2005; Gehler et al., 2016]. And more recently, Wordsworth et al. [2017] have shown that significant warming of early Mars could have been affected by CO_2-CH_4 collision-induced absorption. Thus, determining how much methane exists and rates of release would be important input for Mars climate studies.

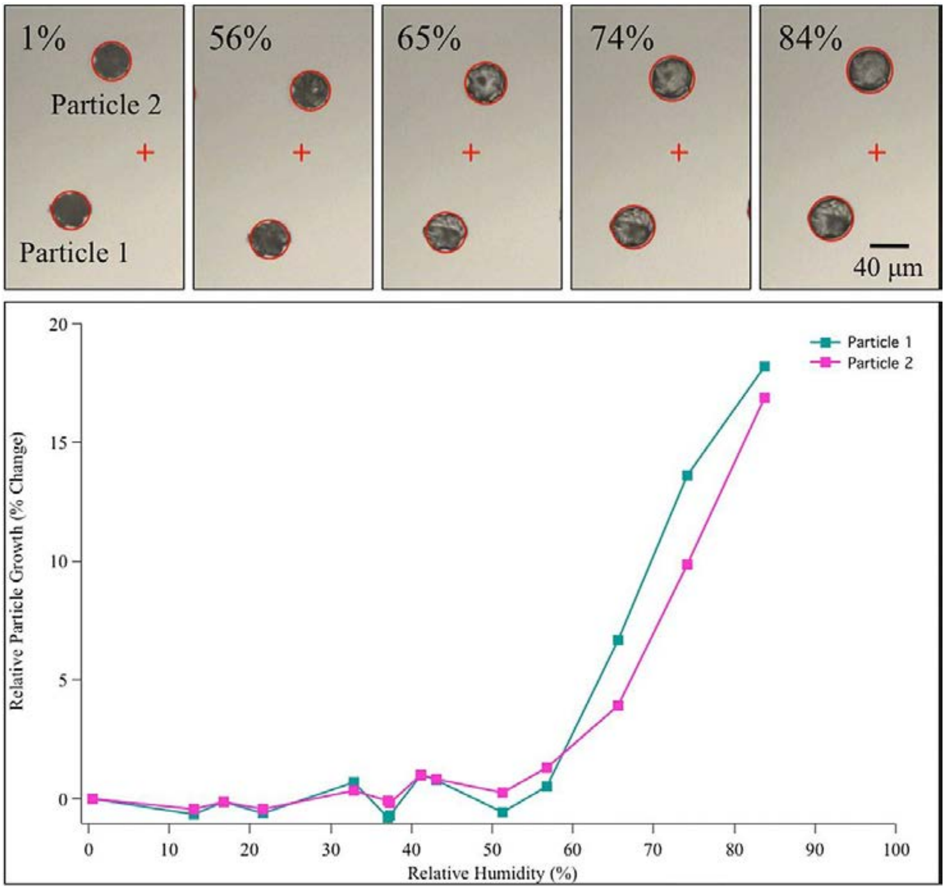


Figure 2.6. *Example of experimental work with Mars simulants, to determine the conditions under which water and regolith materials may interact, enabling identification of resultant observable chemical or geomorphological changes. Figure is from Nuding et al. [2015], and shows particle growth as a function of increasing relative humidity. For this experiment, the "Instant Mars" salt analog simulant was developed to closely match the individual cation and anion concentrations at the Phoenix landing site as reported by the Wet Chemistry Laboratory instrument. At the top are two Instant Mars particles shown at different stages of deliquescence; at the bottom, their growth at a relative humidity greater than 64% indicates ready uptake of water.*

Additionally, methane is likely to be *indirectly* related to Martian water ice, as water ice can seal subsurface accumulations of methane in conventional reservoir rocks or store it within the lattice of frozen water molecules in clathrates [Max et al., 2013; Oehler & Etiope, 2017]. Release of gas to the atmosphere from ice-sealed accumulations or clathrates could occur by depressurization, such as might occur in areas of erosion, ice sublimation, recent impacts or faulting that could fracture or breach a seal or release pressure from clathrates. Similarly, temperature increases can destabilize clathrates and such increases might be associated with magmatic intrusion, venting of gas from depth that may also convey heat [Max et al., 2013], or seasonal or obliquity-related changes [Kite et al., 2017]. These types of effects could account for episodic releases of methane to the atmosphere from subsurface deposits [Etiope & Oehler, 2019].

However, the distribution of subsurface methane on Mars is not known. Methane spikes, plumes, and seasonality in background values have been reported [Formisano et al., 2004; Mumma et al., 2009; Geminale et al., 2011; Webster et al., 2015; 2018], though debate has continued regarding the validity of these measurements. Recent work suggests that episodic methane spikes are geologically reasonable for Mars [Etiope & Oehler, 2019], and the independent detection of a methane spike observed by MSL in 2013 by the Planetary Fourier Spectrometer on the Mars

Express orbiter argues for the reality of such releases [Giuranna et al., 2019]. The 2019 work of Giuranna et al. additionally points to a source location for the detected 2013 methane spike in the Medusae Fossae Formation (MFF), where faults of Aeolis Mensae appear to extend into the region of proposed, MFF shallow water ice [Wilson et al., 2018] and may episodically release gas trapped within or below the ice. Nevertheless, early observations by the Trace Gas Orbiter on the ExoMars spacecraft show no evidence of methane above the TGO detection limit of ~ 50 pptv (Korablev et al., 2019). The implications of this result are currently under investigation. Previous work has addressed processes of methane sequestration or chemical destruction [e.g., Lefévre & Forget, 2009; Knak Jensen et al., 2014; Holmes et al., 2015; Lefévre, 2019, Moores et al., 2019] that might result in atmospheric methane lifetimes of less than the ~300 years predicted for Mars from photochemical loss [e.g., Yung et al., 2018], and continuing investigations of such processes are in progress.

Locating the sites of methane releases will be a first step towards understanding of the origin and significance of methane on Mars. Orbital, telescopic or near-surface detections (like those on MSL) can then be tied to locations of likely surface release by a combination of climate modeling and geologic assessment [e.g., Giuranna et al., 2019]. To date, this has only been done for the methane spikes detected in June of 2013 at Gale crater. From there, future ground-based investigations (using soil gas and closed-chamber methods, as are commonly used on Earth) of predicted locations of surface release can offer less ambiguous results than atmospheric measurements, because these methods allow capture of higher concentrations of methane and minimize atmospheric fractionation so that isotopic studies will be more meaningful.

2.3 Atmosphere State and Dynamics

2.3.1 Atmospheric circulation and cycles

The Martian climate is controlled by the seasonal cycles of dust, water, and CO_2, which are coupled through atmospheric circulation patterns. Atmospheric circulations on scales ranging from local to global control the transport of heat, momentum, dust, volatiles, and trace gases through the Martian atmosphere and between their respective surface sources and sinks. The transport of dust and volatiles into and out of the polar regions and between non-polar reservoirs are of primary interest for understanding how polar and non-polar ice deposits form.

As CO_2 is exchanged seasonally between the atmosphere and the surface, resulting in the growth and retreat of seasonal polar caps, it is modified by (and modifies in turn) both atmospheric water and dust [e.g., Titus et al., 2017 and references within]. The seasonal water cycle is characterized by a repeatable exchange between the surface reservoirs, most notably the exposed north polar cap, and the atmosphere. As it sublimates from the north polar cap in northern spring, water vapor is advected southward by the topographically modulated, overturning global circulation, condensing as a seasonally recurring cloud belt near the equator in northern spring and summer [e.g., Clancy et al., 1996] (because northern summer occurs at aphelion, this is known as the "aphelion cloud belt"). Water ice clouds are radiatively active, affecting temperature profiles that in turn influence surface ice accumulation and strengthen the overturning Hadley circulation [e.g., Navarro et al., 2014]. Dust is lofted from the surface by both convective vortices (i.e., dust devils) and wind stress, the latter of which can develop into dust storms that range in scale from kilometers to planet-encircling. The lofted dust absorbs heat, affecting the thermal structure of the atmosphere, which in turn influences the atmospheric circulations that can lead to further dust entrainment. Lofted dust interacts with the water cycle as dust grains provide cloud condensation nuclei; a dusty atmosphere interacts with the CO_2 cycle by enhancing heat transport into the polar regions where CO_2 condenses and precipitates at the surface [e.g., Kahre et al., 2017]

Spacecraft observations have provided some insight into global circulation patterns, e.g., revealing Hadley cells and strong thermal winds [e.g., Smith, M.D., et al., 2001]. However, our understanding of the circulations responsible for transport mainly relies on numerical models because global wind fields have never been directly and systematically measured. The general circulation consists of large-scale mean and eddy circulations [e.g., Barnes et al., 2017]. The seasonally varying mean overturning circulation (the Hadley cell) results from the global asymmetric seasonal heating of the atmosphere. Models suggest that two comparatively weak Hadley cells share a common rising branch near the equator during equinoctial seasons, and a single stronger cross-equatorial Hadley cell dominates during the solstices. The Hadley cell is thought to be of primary importance for cross-equatorial transport [e.g., Montmessin et al., 2017]. The thin Martian atmosphere and its strong coupling to the surface results in strong sun-synchronous (migrating) thermal tides that are likely to give rise to significant non-migrating eastward and westward components due to topography and non-uniform radiative heating. The migrating semi-diurnal tide is particularly important because it is amplified with increasing global dust loading and it may thus play a role in the genesis of global dust storms [e.g., Lewis & Barker, 2005; Zurek, 1981]. Finally, transient and stationary eddies are thought to primarily arise from baroclinic instability of the mean flow and from longitudinal variations in surface topography, respectively. Transient and stationary eddies are critical for the meridional transport of dust and volatiles, particularly into and out of the polar regions [e.g., Montmessin et al., 2017].

Changes to Mars' orbital parameters (obliquity, eccentricity, season of perihelion) over time affect the Martian climate system through the modification of solar insolation, and thus largely control the formation and evolution of surface ice deposits. Global climate models have been used to understand the impacts of changing orbital parameters on the general circulation and on the CO_2, dust, and water cycles [e.g., Fenton & Richardson, 2001; Forget et al., 2006; 2017; Haberle et al., 2003; Levrard et al., 2007; Madeleine et al., 2014; Mischna et al., 2003; Newman et al., 2005]. Obliquity has the most significant effect because it directly controls the latitudinal distribution of insolation. At low obliquity, we expect the atmospheric pressure to be reduced compared to the current epoch due to the formation of permanent CO_2 ice caps at the poles where insolation is low. This reduction in atmospheric mass, combined with a reduced latitudinal temperature gradient between the spring/summer and fall/winter hemispheres, likely leads to a weak mean overturning circulation. To first order, the weak circulation and reduced surface pressure will result in a weak dust cycle.

As obliquity increases, models indicate that the increased cross-hemispheric temperature gradient drives a strong intensification of the Hadley cell, which results in stronger near-surface flow in the return (near-surface) branch. Eventually, this strong mean overturning circulation dominates over other components of the general circulation (e.g., transient eddies). At moderate obliquity (>35°), water becomes stable in the middle latitudes and the atmosphere is likely significantly wetter than at low obliquity [Jakosky & Carr, 1985]. The enhanced circulation increases the potential for dust lifting.

At high obliquity, models robustly predict that, when dust is assumed to be infinitely available planet-wide, dust lifting increases dramatically due to the strengthened Hadley cell, which is further intensified by dust radiative/dynamical feedbacks (Haberle et al., 2003; Newman, 2002). Water ice is destabilized at the poles and becomes stable at low latitudes. The locations of low-latitude ice deposits are likely driven by snowfall resulting from topographic forcing (Forget et al., 2006). Key current research areas include investigation of the role of finite dust reservoirs on the current and past dust cycles, and isolating the effect of water ice clouds on the climate over time through radiative and microphysical feedbacks. A complete understanding of how orbital variations affect cycles of dust, H_2O, and CO_2 is critical for understanding how surface ice deposits form, evolve, and ultimately record the history of Martian climate.

2.3.2 Present key atmosphere constituents and meteorology

Meteorological observations of the Martian atmosphere from orbit have been made as far back as the Mariner program in the early 1970s [Leovy et al., 1972]; landed assets have made complementary measurements beginning with the first landing of Viking in 1976 [Hess et al., 1977]. Presently, a fleet of orbiting and landed spacecraft is making measurements of the atmosphere, adding to a continuous, 20+ year record. This outstanding dataset has taught us much about the Martian atmosphere, but because the quality, coverage and type of measurement have varied, and because certain key measurements have yet to be made, the overall atmospheric record remains incomplete. Studies, too, that rely on this atmospheric information go unfinished. In particular, our ability to map out the history of Mars as written in the PLDs and other ice reservoirs depends on understanding the circulation and transport of volatiles. Without adequate measurements, and the correct type of measurements, interpretations of Mars' historical record remain inconclusive.

Existing measurements of the Martian atmosphere provide valuable information about its state and behavior on diurnal, seasonal, annual and even interannual timescales. Measures of surface pressure, surface and air temperature, humidity, wind and radiation have been obtained over the past several decades with varying levels of fidelity and coverage [e.g., Davy et al., 2010; Gómez-Elvira et al., 2014; Schofield et al., 1997; Sullivan et al., 2000]. Orbital assets can provide near-global coverage of the planet, but at the expense of temporal resolution and precision. Conversely, landed assets can provide high temporal resolution at a specific landing site, but lack any broader spatial information. In conjunction with numerical models of the atmosphere, we have been able to reconstruct, piecemeal, the basic 4-D structure of the Martian atmosphere, and a general sense of its dynamical and physical behavior.

Available for comparison with models, many instruments on orbiters have obtained vertical profiles of atmospheric properties (e.g., MCS, TES, CRISM) at levels above 10 km. For example, middle atmosphere temperatures from ~10–80 km have been obtained from several orbiting spacecraft with reasonable spatial coverage [e.g., McCleese et al., 2010; Smith, M.D., et al., 2001]. Most available data, however, are restricted to specific times of day based upon the spacecraft orbit. Further, observations from orbit, to date, have had a limited ability to peer 'inside' dusty atmospheres (those with opacities ε1), and so environmental conditions in and around dust storms are not well known. In addition, there is a marked dearth of information within the boundary layer (lowest ~10 km, §2.4.1), apart from observations of the surface layer (10s of meters) from a few systems placed on the ground, as orbiting assets cannot effectively see to those low altitudes. Spatial and temporal gaps in some of these measurements can be estimated with the use of general circulation models (GCMs) and mesoscale models, which are capable of reproducing global atmospheric conditions, and which compare reasonably well to observations [e.g., Greybush et al., 2012; Steele et al., 2014]. However, these models remain unvalidated against some key measurements, such as atmospheric winds.

The trace gas composition of the Martian atmosphere has been observed both remotely (from Earth) and from spacecraft at Mars. Of particular interest is characterization of water vapor in the

Martian atmosphere. The vertical distribution and transport of water vapor have implications for the long-term stability of subsurface ice and for polar deposit history. To date, the global mean annual water cycle has been observed in a column-integrated sense (i.e., column abundances of water vapor have been measured) sporadically with Earth-based telescopic observations since 1963 and with orbiting spacecraft since 1997 as well as previously by the Mariner 9 and Viking spacecraft. From this information, we can quantify how much water is typically sublimed off the primary surface water source (the NPRC) into the atmosphere, and we have some sense of where that water is carried through observations of changing water column abundances with time. However, there is little information about the vertical distribution within this water vapor column. ESA's ExoMars Trace Gas Orbiter has the capability of profiling water vapor through regular, spatially limited, solar occultation measurements, though not at high polar latitudes from where most of this atmospheric vapor is derived. The near-surface relative humidity has also been measured by the landed spacecraft, but measurements drop below the detectable limit during the warmer daytime hours. A more practical measure of water vapor content during the day is absolute humidity (or mixing ratio); however, there is limited information on the absolute humidity near the surface where a large percentage of the column water resides. High absolute humidity values near the surface would have significant implications for the stability of subsurface ice and net loss/gain of vapor from/to the region (as well as the deliquesced brine and salt hydrate stability).

Water ice in the Martian atmosphere has been observed from orbit via visible imaging [e.g., Wang and Ingersoll, 2002], infrared measurements [e.g., Tamppari et al., 2000], and LiDAR [Pettengill and Ford, 2000]. From the surface, water ice has been detected with similar techniques, and with a lander-based upward looking LiDAR on the Phoenix lander (Fig. 2.7) [Whiteway et al., 2009]. Condensed water in the atmosphere is important, as it is diagnostic of inhibited water vapor transport that occurs seasonally on Mars [Clancy et al., 1996]. Atmospheric water ice, seen both in clouds and near-surface fogs, has been observed since before the spacecraft age [e.g., Smith and Smith, 1972]. Column abundances of atmospheric water ice and some cloud heights were obtained using Viking orbiter data [e.g., Tamppari et al., 2000]. Since the modern continuous spacecraft record began in 1997, synoptic views by wide-angle cameras and column abundances of water ice and, later, their vertical profiles between ~20–80 km have been obtained [Clancy et al., 2017]. To

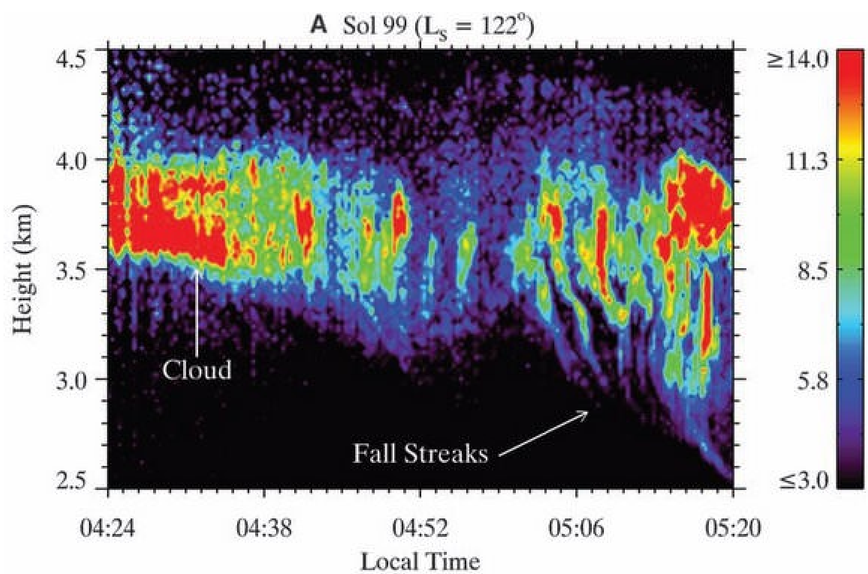


Figure 2.7. *Observation of Martian clouds over the Phoenix landing site. Contour plots of backscatter coefficient (×10^{-6} m^{-1} sr^{-1}) derived from the LiDAR backscatter signal at wavelength 532 nm on mission sol 99 (L_s = 122°, Mars year 29). Signal shows presence of water ice cloud between 3.5–4.0 km and fall streaks descending from the height of the cloud towards the ground. Image is from Whiteway et al. [2009].*

date, all of these measurements have been obtained from spacecraft with polar orbits, yielding nearly fixed time of day coverage (e.g., 3 AM/PM), or from spacecraft with highly elliptical orbits, yielding good resolution but limited spatial/seasonal coverage.

Continued atmospheric water ice measurements would benefit the long-term record, allowing for more insight into the present-day climate and weather variability. Additionally, these and water vapor data are needed for a full accounting of the atmospheric water budge and to relate the seasonal water cycle to the obliquity cycle. Based on Earth-based observation [e.g., Jakosky and Barker, 1984] and more recent orbital observations [e.g., Khayat et al., 2019; Smith, 2002], the water vapor cycle has been shown to vary significantly through seasons and Mars year; unfortunately there is a dearth of vertical profiles of water vapor over the full range of diurnal and seasonal variation, over the Martian globe, for tracking the amount and variation of water vapor in the Martian atmosphere at higher-resolution.

Dust has been widely observed both from the ground and orbit. Martian dust can exist as a fine haze (Fig. 3.2) or as thick, large dust clouds, up to global scale in extent. There are regularly observed dust storm 'tracks' from where many storms originate [Hollingsworth et al., 1996; Wang & Richardson, 2015]. The height of these clouds can be estimated from shadows cast on the surface (for optically thick clouds), as well as from thermal measurements (for more optically thin clouds). Smaller-scale storms generally follow a repeatable interannual pattern — most storms occur during the southern summer months, and regional storms regularly occur at the same season year after year along defined storm tracks [e.g., Wang & Richardson, 2015]. The larger, global-scale storms, however, occur infrequently, and there is no widely accepted mechanism known to be responsible for this interannual variability [e.g., Kahre et al., 2017].

2.4 Surface Environment and Processes

2.4.1 Boundary layer meteorology

Understanding the Martian planetary boundary layer is fundamental to understanding both polar and climate science on Mars. Within this near-surface region, there is more vigorous turbulence and small-scale atmospheric structure than at higher altitudes, and the interaction of the atmosphere with the underlying surface over all scales is important for understanding surface-atmosphere volatile exchange and dust lifting and transport. Global-scale circulations (§2.3.1) convey ice and water vapor from source to sink, while the migration of volatiles from one surface reservoir to another occurs mainly through atmospheric transport within the boundary layer. Local conditions within environments close to the surface ultimately determine where, at what rate, and to what depth volatiles accumulate in polar deposits and non-polar ice reservoirs [e.g., Montmessin et al., 2017].

Likewise, near-surface winds entrain dust from the surface and carry it up through the boundary layer, to altitudes of many tens of kilometers. On Mars, suspended dust is a major climate forcing agent, primarily due to local heating through absorption of shortwave solar radiation [e.g., Kahre et al., 2017; Zurek et al., 1992]. The resulting changes in air temperature affect winds and relative humidity throughout the atmospheric column, which in turn change patterns of volatile and dust exchange with the surface. In this manner, volatiles and dust are intimately linked to the Martian climate system through complex positive and negative feedbacks. Ice reservoirs at the poles and elsewhere provide a long-term record of these interacting processes through time.

Wind and eddy fluxes within the planetary boundary layer

Wind velocities on Mars are poorly known within the boundary layer, with only limited measurements from some landed spacecraft (*Viking*, *Pathfinder*, *Phoenix*, *MSL*, and *InSight*). These missions were limited in geographic and altitude sampling and sometimes in mission duration. *Mars Pathfinder* and *Phoenix* had simple “wind-sock” type measurements that did not provide a continuous record, and both were missions of limited duration (83 and 157 sols, or 12.4% and 23.4% of a Mars year’s length, respectively); additionally *Pathfinder*’s hot wire anemometer was not adequately calibrated so provided only relative measurements. One of two wind sensors on *MSL* was irrecoverably damaged upon landing and so only semi-quantitative measurements of wind direction and speed are available, and only in certain spacecraft orientations. Some Earth-based wind measurements have been made, but at isolated seasons and locations [Sonnabend et al., 2006; 2012]. The InSight wind measurements, recently begun, are showing good results [Banfield et al., 2019; Newman et al., 2019], but again, these measurements are limited to one location on Mars.

With the exception of these few in situ measurements, the boundary layer wind field of Mars is understood mainly from numerical models (global climate models, mesoscale models, and large eddy simulations), and from observable aeolian features that may reflect only the strongest near-surface winds, though with loosely constrained timing. Numerical models are used to calculate the wind field for spacecraft entry, descent, and landing (EDL), and for many climate-related studies, but because they have not been adequately constrained by observations, different models often produce markedly different wind profiles for the same location and time. Direct data are needed to validate model results.

At present, the meteorology instrument suites included on landed missions have not provided a quantitative data set suitable for addressing many knowledge gaps in climate science, and thus interpreting the volatile records. Turbulent near-surface winds regulate the flux of water vapor, dust, heat, and momentum from the sinks at (and below) the surface to higher levels of the atmosphere [e.g., Jakosky et al., 1997; Tillman et al., 1994]. This process controls a significant part of the response of surface and near-surface ice reservoirs to seasonal, interannual, and climatic changes. As discussed above, in order to properly understand the current climate and historical climate record, a good understanding of vapor and dust transport is needed, which requires knowledge of the wind field and global circulation (§2.3.1).

Temperature and pressure

The surface temperature of Mars, and therefore its climate state, is determined through the balance of several forcing terms, including downward shortwave heat flux (insolation), upward shortwave heat flux (reflected insolation), downward longwave heat flux (atmospheric emission), upward longwave heat flux (surface and atmospheric emission), latent heat flux from volatile phase change in the atmosphere or at the surface, and sensible heat flux produced by turbulent eddies. Although landed missions have included instruments that measured some of these terms (e.g., surface temperature), no meteorology station has included a comprehensive suite of instruments capable of constraining these forcing terms (§3.1.1). Surface and near surface (~1 m) temperatures have been measured by landed assets, but temperature profiles spanning the range between the surface and ~10 km (§2.3.2) are not known.

Surface pressure is first set by elevation, and with knowledge of the elevation of the landing site and assumption of hydrostatic equilibrium in the atmosphere, a general 3-D ‘map’ of global surface pressure can be derived. The global seasonal cycle is driven by the seasonal condensation and sublimation of the CO_2 polar caps; this has been observed to influence surface pressure by as much as 25% over the course of the Martian year [Genova et al., 2016; Wood & Paige, 1992] by the Viking landers (22°N and 48°N) and MSL (4.5°S). However, a full annual pressure cycle has not yet been observed at latitudes where the seasonal CO_2 cap extends, and localized condensation and sublimation may drive higher-order surface pressure changes.

Diurnal variations in surface pressure, a consequence mainly of atmospheric tides and topography, are less well known in locations away from the surface landers, but they are significant, and can introduce as much as a 10% variability in surface pressure over the course of the day at any one location [Haberle et al., 2014]. Because pressure and wind are intimately tied together, pressure measurements are an essential component of any meteorological station. At a minimum, these types of measurements are needed to aid in safely landing spacecraft on the surface (and have been used for this purpose).

Atmospheric boundary layer profiles

An understanding of the transport of volatiles and dust requires knowledge of the three-dimensional concentration of aerosols throughout the atmosphere, particularly at locations near sources and sinks at the surface (i.e., within the planetary boundary layer). Although measurements of aerosol optical depth and column water abundance commonly derived from lander data are informative, these data sets do not contain information about the vertical distribution of aerosol concentration. As discussed in §2.3.2, orbiter-derived profiles do not typically reach down into the planetary boundary layer and generally do not span a range of local times. The Phoenix mission LiDAR provided the first upward-looking aerosol profiling that revealed weather-induced variations of clouds and dust layers, as well as the first direct measurement of the planetary boundary layer depth [e.g., Tamppari et al., 2010].

The near-surface water vapor content is a fundamental control on the deposition and removal of ice and formation of liquid [e.g., Leighton and Murray, 1966; Ingersoll, 1970] and, therefore, is a key factor in the link between the atmosphere and surface components of polar and climate science. At present, most information on this parameter is derived from orbital instruments that provide limited vertical resolution or temporal information [e.g., Smith, M.D., 2008] and models of planet-wide ice stability rely on various schemes for inferring this information. However, Phoenix lander observations suggested that water vapor may not be well-mixed [Tamppari et al., 2010]. Phoenix also provided the first direct measurements of the humidity at the surface, but those may have been influenced by sublimation of the ice exposed during the landing [Zent et al., 2016]. Earlier measurements inferred to be near-surface water-vapor abundances were derived from the Viking landers [Jakosky et al., 1997; Ryan et al., 1982], and humidity has since been measured by *MSL* as well [e.g., Harri et al., 2014], but over a largely desiccated surface [Jun et al., 2013].

Sand and dust transport

Sand saltation may be the primary mechanism to lift the dust that colors the Mars sky, acts as nucleation centers for ice aerosols, interacts radiatively to adjust temperature profiles and redistribute heat throughout the atmosphere, and falls back to the surface to be either lofted again or stored in sedimentary deposits such as polar caps [e.g., Kok et al., 2012]. Further, the bombardment of saltating sand may be the most effective agent currently eroding the Martian surface, exhuming ancient terrains that reveal the geologic record and which potentially harbor long-buried biosignatures [e.g., Farley et al., 2014]. While the movement of many aeolian bedforms (i.e., ripples and dunes) have been tracked from orbit and used to estimate sediment fluxes [e.g., Bridges et al., 2013], in situ measurements of sediment fluxes, correlated to local (in time and space) meteorological conditions, have rarely been collected (some observations have been collected by *MER Spirit* [Sullivan et al., 2008] and *MSL* [Baker et al., 2018; Bridges et al., 2017]). This has been frustrating as models of sediment flux have often predicted that wind speeds higher than observed wind speeds are needed to generate saltation. Much of our understanding of aeolian transport of particulates on Mars has been determined through numerical models and wind tunnel experiments which seek to resolve this discrepancy. Recent work suggests that the differences between prediction and observation of wind-driven sand flux are likely due to saltation on Mars being, in many ways, fundamentally different from that on Earth [e.g., Kok, 2010; Lapotre et al., 2016; Sullivan and Kok, 2017].

2.4.2 Seasonal frost

Seasonal evolution of the surfaces in the Martian polar regions has been monitored for over a decade by various instruments on a suite of orbiting spacecraft. Mapping of the seasonal presence of H_2O and CO_2 ices on the Martian surface informs us about the Martian climate today and the current formation of surface icy deposits, which is a crucial part of understanding the accumulation and evolution of icy deposits in Martian past climates. A seasonal ice layer is observed to form in the winter hemisphere starting in the fall and lasting through early spring. The seasonal ice layer is mainly composed of CO_2 ice [Kieffer et al., 1976; Langevin et al., 2007] with inclusion of smaller amounts of H_2O ice [Bapst et al., 2015; Jakosky, 1983] and mineral dust [Vincendon et al., 2008]. It forms by direct surface deposition [Brown et al., 2014; Langevin et al., 2007; Titus et al., 2001;] or snowfall [Hayne et al., 2014; Ivanov & Muhleman, 2001; Titus et al., 2001]. The proportion of CO_2 formed by direct deposition versus snowfall plays an important role in regulating the seasonal behavior of the CO_2 layer, including its recession rates, but these are currently unknown.

The maximum thickness of the seasonal layer varies spatially depending on the local topography but generally follows a trend of increased thickness towards the pole. The seasonal layer extends down to latitudes of approximately 50° [Aharonson et al., 2004; Kieffer et al., 2000; Kieffer & Titus, 2001; Piqueux et al., 2015] with some local transient CO_2 frosts observed at night down to the equatorial latitudes [Piqueux et al., 2016]. The characteristics of this ice layer, such as density and grain size evolution, remain a source of debate; considerable variations in the seasonal CO_2 layer density through both the winter season and inter-annually have been observed [Matsuo & Heki, 2009]. Laboratory investigations indicate that CO_2 frost turns into slab ice during winter deposition and that slab ice cracks extensively and thus displays more frost-like optical and thermal properties (Fig. 2.8) [Portyankina et al., 2019]. The exact behavior and state of CO_2 ice largely depends on the local weather conditions and the presence and amount of inclusions, such as dust and H_2O crystals. Thus, the physical and thermal properties of ice are expected to vary diurnally, seasonally and inter-annually. The variations in CO_2 density observed during one season [Matsuo & Heki, 2009] could be attributed to a seasonal sintering process [Eluszkiewicz, 1993], while interannual variability is thought to come from variable amounts of dust deposition due to local or global dust storms, which are more pronounced in some years.

The seasonal cap maximum extent and the timing of cap growth and recession should exhibit some degree of interannual variability in response to interannual atmospheric variability, such as the presence of global dust storms [Benson & James, 2005; Bonev et al., 2002, 2008; Haberle et al., 2008; Kahre & Haberle, 2010; Piqueux et al., 2015]. Both hemispheres show data that are consistent with the presence of an H_2O ice annulus during seasonal cap retreat extending to up to 6° equatorward of the edge of the retreating CO_2 ice [Appere, et al., 2011; Kieffer & Titus, 2001;

Wagstaff et al., 2008]. Water frost is also expected to be redistributed seasonally at the local scale, in response to CO_2 ice sublimation and other interactions of CO_2, H_2O and dust. This is important for studies of surface change, as interactions between frost and the surface appears to drive much geomorphological activities (§2.4.3).

The annual cycling of the seasonal cap should leave a sublimation lag, composed mainly of dust and H_2O ice. The majority of the H_2O ice will also sublime (as observed by e.g., Wagstaff et al. [2008]), but some likely remains either as a thin layer beneath the fresh, dusty sublimation lag or as adsorbed water on the dust grains. The amount of water in this fresh sublimation lag may also be altered through diffusive processes. Therefore, the thickness and composition of the annual lag (that may form an annual "layer" within the PLD) will vary depending on the global (e.g., global dust storm during the condensation phase) and local conditions (e.g., humidity during the summer) during the year. It would be these annual lags, building up over centuries or millennia (not necessarily monotonically), that presumably form the thicker PLD layers that are seen from orbit (§2.1.1).

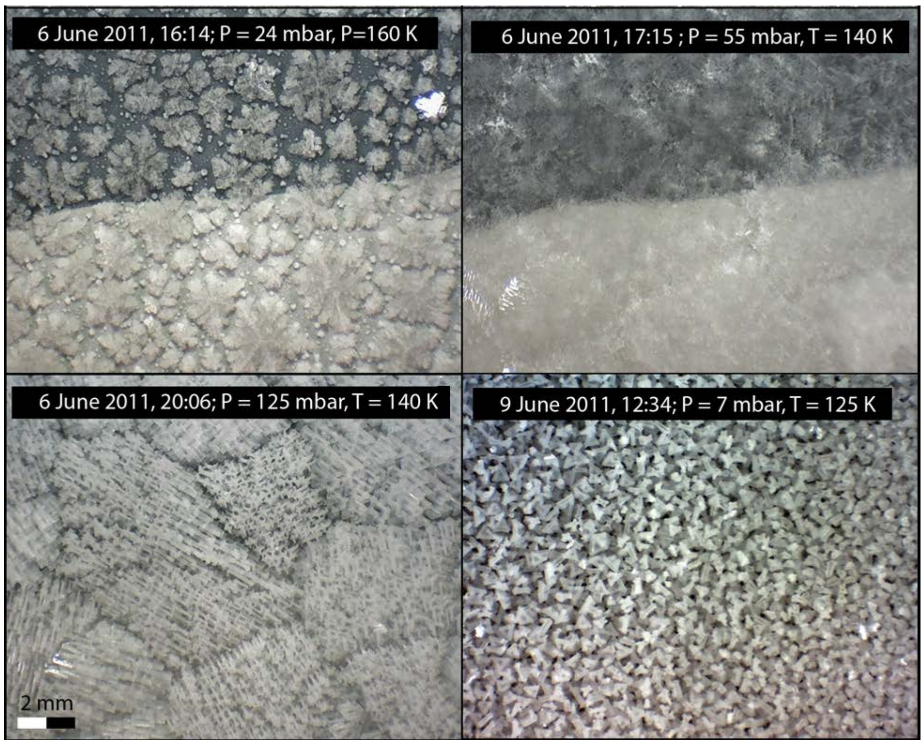


Figure 2.8. *Microscopic images of four different textures of CO_2 ice formed on top of the cooling plate in laboratory settings under conditions similar to those expected in the Martian polar regions: (from top-left and clockwise) CO_2 crystals resembling snowflakes, semi-translucent continuous slab, multi-crystal CO_2 ice shaped as flat hollow triangular prisms, and regions of "directed crystals." The variety of CO_2 ice forms and processes that govern the transitions between them are of high importance for understanding the seasonal evolution of the polar regions and polar ice interactions with the current and recent climate. Figure adapted from Portyankina et al. [2019].*

2.4.3 Surface activity

Based on repeated high-resolution imaging of features over seasonal and annual timescales, widespread, active changes on the surface have recently been observed across Mars. Much of this activity appears to be driven by volatile ices, thus tying investigation of surface changes and related landforms to investigations of the Martian ice and climate systems. Here we summarize current information about observed surface activity driven by volatiles or the atmosphere; investigations of impact cratering and volatile-free mass wasting are not discussed, but these processes are also ongoing and widespread.

Aeolian processes occur planet-wide and are a major agent shaping the modern surface. Dust storms can reach regional or planetary scales, and regional-scale albedo changes have been documented on timescales of decades [e.g., Geissler et al., 2016]. In addition to the direct effect on the surface, dust lifting (§2.4.1) is also an important part of the climate system because aerosol dust influences atmospheric heating. Sand saltation (§2.4.1), with associated migration of dunes and ripples at scales large enough to be seen from orbit, is also now known to be a global process [Bridges et al., 2013]. These findings have led to new models for the basic operation of saltation and grain movement [e.g., Sullivan & Kok, 2017]. Understanding modern aeolian processes is necessary in order to interpret their past effects in moving sediment and volatiles around Mars and in sculpting the surface, creating landform-records of specific climate conditions or exposing volatile reservoirs.

The seasonal CO_2 cap has major effects on the surface during sublimation. When transparent or translucent, the frost sublimes at the base, allowing gas pressure to rise and eventually vent to the atmosphere, carrying trapped sand and dust with it [Kieffer, 2007]. This frost-driven activity results in a variety of spots and flows on the surface, as well as eroding enigmatic landforms called araneiforms (and commonly referred to as “spiders”) [Piqueux et al., 2003] that have been shown to be extending today at scales resolvable by HiRISE [Portyankina et al., 2017]. Early phases of the seasonal frost layer also may drive activity; for example, alcoves at the brink of north polar dunes appear to form soon after frost first appears [Diniega et al., 2018], potentially driven by an interaction between early snowfall and surface frost [Hansen et al., 2018]. Determining the specific environmental conditions and processes that lead to formation of landforms would enable such landforms to be used as proxy markers of those conditions and processes. Then, mapping of those landforms would generate a new type of global map of local-scale present-day environmental conditions.

Present-day activity in Martian gullies [Malin et al., 2006] also reflects the action of seasonal frost [e.g., Diniega et al., 2010; Dundas et al., 2017a]. Present-day changes are associated with seasonal CO_2 frost and have been shown to incise channels and produce lobate deposits resembling wet debris flow lobes [Dundas et al., 2017a] (Fig. 2.9). This has led to ongoing debate over whether such CO_2 frost processes could be entirely responsible for the formation of gullies, or whether aqueous processes were also involved in a different climate of the geologically recent past [e.g., Dundas et al., 2017a; Conway et al., 2018]. This question has important implications for Mars’ climate history, because aqueously formed gullies would require substantial runoff and imply much warmer and wetter conditions than a CO_2 frost model.

Controversy also exists over the role of water in Recurring Slope Lineae (RSL) (Fig. 2.9). These dark flows recur annually on steep slopes, and grow over a period of months during warm seasons before fading [McEwen et al., 2011]. This behavior is reminiscent of liquid seeps, but no source of liquid is known. RSL terminal slopes are consistently at the angle of repose for sand, suggesting that they are fundamentally granular flows [Dundas et al., 2017b], possibly triggered by the loss of volatiles. However, this mechanism is not fully understood and some continue to discuss wet models [e.g., Stillman and Grimm, 2018]. Conclusive identification of flowing liquid water under modern Martian conditions would have major implications for the present and past Mars’ climate and volatile cycles.

A final category of volatile-related surface activity is change at the poles. Relevant observed changes include blockfalls and frost avalanches on the icy north polar layered deposits (Russell et al., 2008) as well as growth of pits (“Swiss Cheese”) in the south polar residual CO_2 cap [Malin et al., 2001]. The latter is of interest because of uncertainty in whether sublimation of CO_2 increases the modern atmospheric pressure, or whether it is balanced by deposition elsewhere [e.g., Haberle et al., 2014; Thomas et al., 2016]. Additionally, mixed in with the CO_2 sublimation is release of water vapor, as water ice is mixed in (potentially in discrete patches) with the CO_2. Finally, should the CO_2 cover on the SPRC disappear through the growth of pits and other sublimation processes, the exposed water ice [Titus et al., 2003] could produce an order of magnitude more water vapor in a southern summer season than now occurs in the northern summer season (e.g., potentially the source of a large water vapor pulse in 1969 [Jakosky & Barker, 1984]).

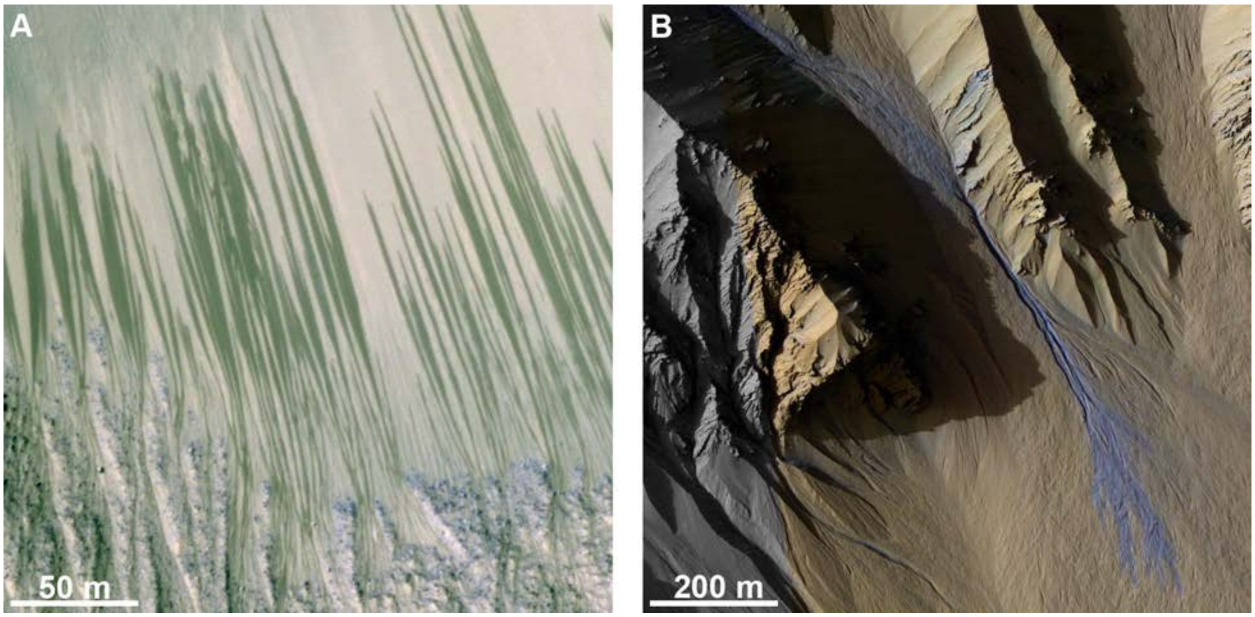


Figure 2.9. *Examples of active surface features observed by HiRISE. A) Recurring Slope Lineae (ESP_027802_1685). The RSL extend downslope, which is towards the top of this image. B) New gully flow with lobate deposits (blue in this enhanced color image; ESP_020661_1440), extending downslope, which is toward the bottom-right in this image.*

3 Compelling Ice and Climate Science Questions, and Needed Measurements

The overall aim of ICE-SAG is to identify ways to advance our understanding of the recent climate history of Mars. Towards this aim, ICE-SAG has developed an extensive list of high-level Mars science questions that relate to ice and climate science (see introduction to §2), and then used these questions to motivate and organize their investigations, tracing the highest priority science areas into mission concepts (§4).

ICE-SAG realized that four categories of questions are integrally involved in the study of Mars' ice and climate — questions that aim to:

- characterize the main ice reservoirs (i.e., determine the current ***State*** of the surface and subsurface ice reservoirs – their locations, volumes, and structure);
- measure and understand volatile transport between the ice reservoirs, atmosphere, and regolith (i.e., estimate the types and rates of mass ***Flux*** between these volatile reservoirs in the present and under past environmental conditions);
- identify and understand the ***Drivers and Processes*** for the movement of volatiles, refractory materials, and volatile-induced activity/alteration of the atmosphere/surface/subsurface (i.e., understand surface/atmosphere interactions involving volatiles and ice, with geologic materials that can leave a record to be studied); and
- determine the history of the ice reservoirs (i.e., understand the ages of and ***Record*** of history within the surface and subsurface ice).

As the study of recent climate history ultimately involves identification and interpretation of ***Records***, the fourth category of questions is often the final goal of Mars' ice and climate investigations as it extends studies of processes and the present towards interpreting and understanding Mars' history. However, these ***Records*** can only be observed in their present ***State*** and this state is the cumulative result of ***Flux*** and ***Drivers/Processes*** – so information related to investigations under all of the top three categories of questions is needed to robustly answer questions of the fourth category. Additionally, we note that addressing many of these questions, but especially those of the fourth type, involves a mix of flight observations, modeling studies of processes, studies to improve our interpretation of observational data, and laboratory/field studies. As will be discussed in this section, ICE-SAG finds the following:

> **ICE-SAG FINDING 2.** Understanding the record left by the recent Mars climate requires investigation of interconnected questions involving ice volume and state, fluxes, drivers, and processes.

Within the broad suite of questions identified (listed in Appendix C), we sought to identify the most compelling avenues of investigation that build from our present knowledge/datasets and appear feasible to address via a flight mission(s) during the decade considered by the next Planetary Science Decadal Survey (i.e., 2023–2032). To identify the areas of highest priority, we considered the set of questions from different perspectives:

- Top-priority questions identified within individual subgroups or questions repeated between subgroups.

- Questions attached to measurements that seem most compelling to each individual SAG member, as well as those that have the potential of yielding the biggest Mars science advancement.
- Which questions would have results that help address other questions.
- Which questions likely require new measurements to be answered (versus a new way of looking at existing observational data).

Through all of these methods, the following five Priority Areas consistently appeared. Note that we do not prioritize between these five Priority Areas, although we did identify higher-priority questions and measurements within each of them (described below).

Questions within **Priority Science Area A: Transport of volatiles, dust, and other materials (e.g., salts and isotopologues) into and out of ice reservoirs** focus on both lateral/vertical transport within the atmosphere (i.e., winds) and the flux at the surface, between the atmosphere and surface/subsurface ice reservoirs. This priority area also includes transport of materials once sequestered into an icy reservoir — processes that affect the readable record. Answering these questions requires investigation of high-resolution localized volatile quantities and fluxes, as well as the transport of volatiles and dust to/from the poles, within the global circulation.

Questions within **Priority Science Area B: Global distribution and volume of subsurface ice** and **Priority Science Area C: Vertical structure of ice reservoirs** relate to both polar and non-polar ice deposits. As with deciphering any geological formation, the first step towards understanding the record of ice accumulation is to map its extent and structure. Constraints on the spatial distribution, amount, and vertical structure of the ice reservoirs would yield key information about the systems and cycles of the Martian global climate and volatile abundance. This information is of importance for both polar and non-polar ice, but new investigations focused on the mid-latitude ice locations, volume, and broad vertical structure were generally ranked higher than comparable investigations of the polar ice, as much less is presently known about these reservoirs, relative to the PLDs. An exception are investigations of the detailed near-surface structure within both PLDs and non-polar ice reservoirs, as little is presently known in either case; and for those investigations the better exposure and higher known contextual information makes the NPLD the main target for generating significant advances in our understanding of climate history.

Questions within **Priority Science Area D: Surface activity and environmental conditions, including throughout the polar night, and how these relate to observable records by forming layers** address key gaps in knowledge about how to determine Mars' recent climate. The surface conditions and processes at the PLD, including integration of volatiles and other material, are what led to the formation of the layers after net accumulation over an unknown number of years (centuries? millennia?). Thus, understanding the connection between present-day frost and dust accumulation, subsequent alteration processes, and the resultant observable layers is key for interpreting that climate record. Understanding this connection also would contribute towards interpretation of the topmost structure of high- and mid-latitude subsurface ice deposits. As has been stated in many other studies, the present is the key to the past. Determining the processes that form a layer is an absolute requirement for understanding what the layers record.

Questions within **Priority Science Area E: Potential evidence of liquid water** within the Amazonian/present-day climate focus on both landforms that may be formed or modified by water, as well as mineralogical/chemical signatures of water. These questions rank highly with regards to their potential for scientific advancement as clear identification of the presence of substantial liquid water in the recent and/or present climate of Mars clearly would have important implications for major astrobiology, climate, geology, and future human exploration questions. However, with our current understanding and available data, it seems that the next large advances would best be made via laboratory or modeling studies (e.g., to investigate water vapor interaction with analog regolith materials: §6.2) and/or targeted missions to landforms that are currently debated as potentially formed via liquid water (such as those described in §4.6).

In summary, these five Priority Science Areas reflect the general importance within Martian climate investigations to interpret two key types of "recent" climate records: the PLDs and the non-polar subsurface ice reservoirs, each of which would yield different types of Martian climate information (Fig. 3.1). The PLDs represent the only places to construct a detailed Martian climate record going back millions of years, at potentially annual resolution, and to understand the processes that make layers in the first place (similar to the importance of polar ice cores for terrestrial climate studies). Additionally, the PLDs may contain isotopic variations that yield information about other (volatile and non-volatile) reservoirs on Mars and potentially offer materials with which to determine absolute ages. The mid-latitude ice deposits offer a chance to understand the formation and subsequent alteration of another ice record that had to form under higher obliquity conditions (although their absolute age is not yet known), thus potentially providing a past-climate "groundtruth" check on Martian climate models. Furthermore, studies of the present-state of mid-latitude ice would yield information about preservation of metastable subsurface ice and non-polar atmospheric transport, both of which are important climate processes that contribute to the polar record.

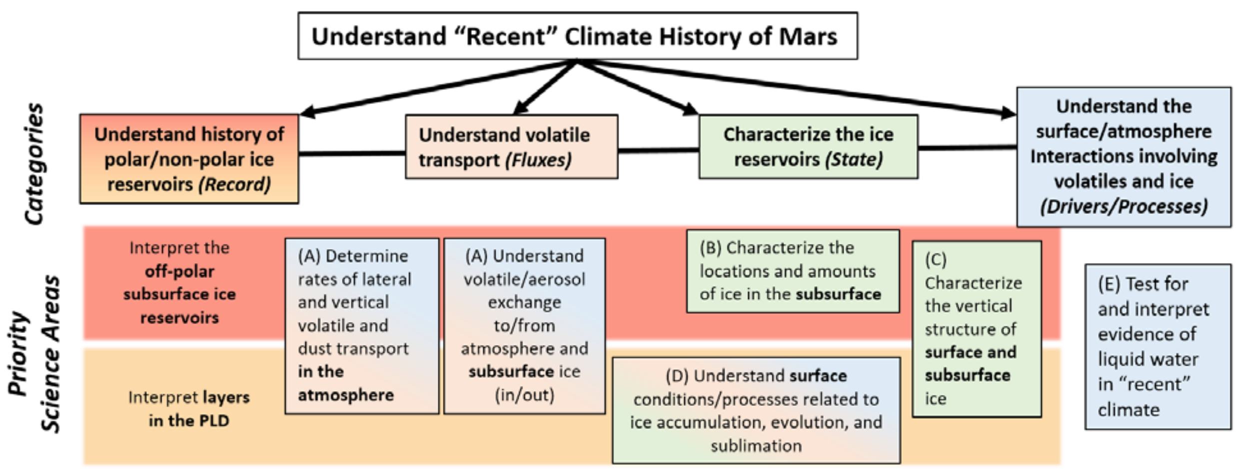


Figure 3.1. *Schematic showing how the ICE-SAG main question (top box) divides into four categories of questions (middle row of boxes, boldfaced text). These categories are all highly connected, and in many cases advances in understanding are needed in all four categories to address a high-priority question about Martian recent climate. Shown beneath the categories are the five ICE-SAG-identified Priority Science Areas (labeled A-E, color coded relative to the Fluxes, State, and Drivers/Processes categories). As discussed in the text, advancements in understanding within these Priority Science Areas (except for E) are necessary for interpretations of the two icy recent climate records (as shown by the red and orange background rectangles and color-coding in the Record category).*

These Priority Science Areas also reflect where we currently lack the right type of data for addressing specific scientific questions. For example, as previously discussed in the NEX-SAG report [MEPAG, 2015], past and existing Martian missions do not yield global or regional wind measurements within the boundary layer, nor water vapor profiles within the boundary layer. Another example is a lack of discrimination of vertical structure (including depth to ice lens/table) within 1–10 m of the surface. A third example is the lack of surface environmental information through the polar night, which is extremely cold and lacks the solar illumination needed for most orbital investigations, but is when seasonal frost is forming, evolving, and exchanging/interacting with the surface. When existing observations are not sufficient to address the compelling science questions, this demonstrates a need for new types of observations, via potentially new instruments flown to Mars and/or technology development to enable new types of missions.

Within this section, we describe the *questions* that relate to these five Priority Science Areas and why we considered them high-priority within Mars ice and climate science. Additionally, we highlight key measurements needed to make substantial progress within each Priority Science Area. Some of those measurements have never been collected before at Mars. Other measurements are continuations of existing measurements that extend the baseline and coverage of observations, or would yield improvements of temporal or spatial resolution and/or coverage over existing measurements. Within both questions and measurement description, we highlight a few that were generally ranked within ICE-SAG as being of the **highest priority —** these are in **boldface** within the text here and are given further attention in §4 as we describe the science objectives of our mission concepts.

3.1 Priority Science Area A: Transport of volatiles and dust into and out of ice reservoirs

The distribution of ice on the surface and subsurface of Mars is controlled, in a major way, by the transport of volatiles and dust in the Martian atmosphere. This transport occurs both at the global scale, with both meridional and zonal winds moving water and dust, and at the local scale, with the exchange of ice between the near surface and the atmosphere. Combined with the spatial distribution of insolation, atmospheric transport determines and maintains the surface ice distribution as a function of the orbital/axial configuration (eccentricity, obliquity, and season of perihelion) and the total inventory of water on Mars. Our understanding of these transport mechanisms remains limited, however, due to limited direct measurements of wind velocity at both global and local scales, and insufficient orbital and near-surface in situ observations of the transport processes and of the sources and sinks of volatiles and dust.

Any investigation into the atmospheric transport and flux rates of volatiles and dust must address *"How does the atmosphere control the exchange of ice and dust between ice reservoirs?"* This question can be separated into two domains: the ***global-scale horizontal and vertical transport*** and the *local-scale vertical transport*. Although these two domains are ultimately linked, the processes and their dynamical timescale differ sufficiently to require different but complementary investigations.

At the global scale, the horizontal and vertical transport connect the large polar ice reservoirs with surface and subsurface non-polar reservoirs. The atmosphere transports volatiles and dust through a combination of the large-scale mean circulation (i.e., the Hadley cell circulation and strong zonal winds) and through macroturbulence mixing (e.g., baroclinic eddies in the mid-latitudes). Both the large-scale circulation and the eddy-mediated circulation transport volatiles and dust poleward from the equator in the present period. However, though we have an initial

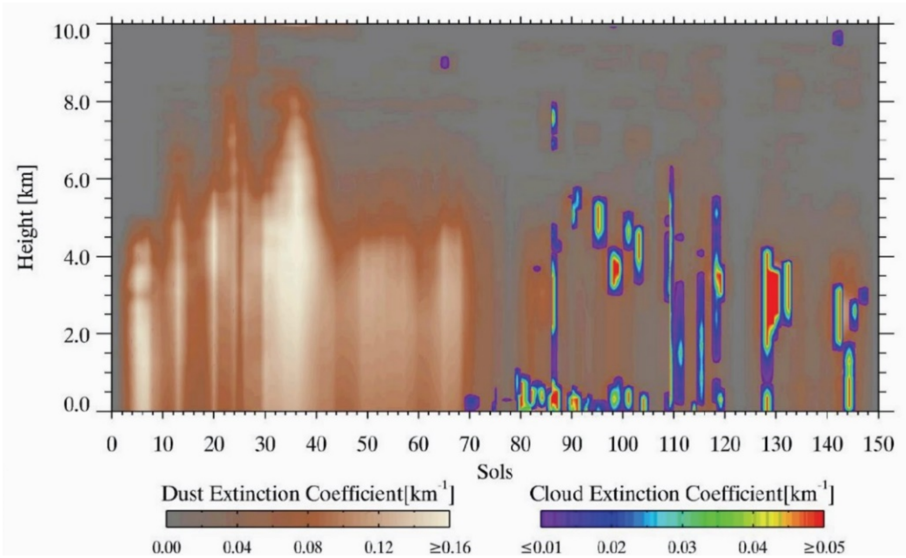


Figure 3.2. *Example of dust being transported from the surface, up into the atmosphere. Contour plot of dust and water ice extinction coefficients derived from the Phoenix LiDAR [Whiteway et al., 2011]. Note the considerable vertical and temporal variations in aerosol distributions.*

theory of both the mean circulation transport and the eddy circulation transport, the modeling of the transport is incomplete and the methodology is biased towards the conditions observed on the Earth. Additionally, we equally lack a deep understanding of the processes that control the formation and location of sources and sinks of volatiles and dust. This combined ignorance demands further investigation into the transport of dust and volatiles into and out of ice reservoirs.

Dust cycles, both annual and interannual, are very poorly understood. Dust sources and sinks are intimately related to past and present climate, and thus answering *"Where are the dust sources and sinks, and how do these connect to the fluxes/distribution of lofted dust?"* (e.g., Fig. 3.2) is required to interpret the variable amounts of dust in the layers of the PLD as signs of past climate. Although both the Thermal Emission Spectrometer (TES) and the Mars Climate Sounder (MCS) have provided both data and initial insights, how the diurnal, seasonal, and multi-annual atmospheric cycles affect and/or control the distribution of ice in the atmosphere and on the surface remains an open question. Over the last few decades, we have begun to understand how the differential heating in the atmosphere and the Martian topography affect the mean circulation on diurnal, season, and multi-annual timescales, but we still lack a complete theory that connects these mean circulations to the macroturbulence circulation, particularly with regard to mid-latitude eddies and dust storms. Both eddies and dust storms can enhance or diminish the magnitude of poleward transport of volatiles and dust, so more measurements are required.

Understanding how the atmospheric cycles affect transport would allow us to understand another key question, ***"What is the current annual net (global-scale) mass flux transport of volatiles, including H_2O and CO_2, and dust from/to polar and non-polar ice reservoirs?"*** More than just understanding the mechanisms for atmospheric transport, we want to understand how much water ice, dust, and other atmospheric constituents are transported annually and the relative transport abundance to each pole. By combining our understanding of both of these two questions (transport due to annual cycles and the net transport of volatiles and material), we would then be able to address the question of how these climate processes control the long-term evolution of polar and non-polar reservoirs, including the formation of the water ice caps, the formation of the residual CO_2 surface ice on the south pole, and the deposition and entrapment of the buried CO_2 ice under the south polar residual cap. Understanding this evolution as a function of the evolution of the orbital parameters (e.g., eccentricity and obliquity) of Mars is critical. Ultimately, answering all of these global questions would provide insight into the transport of ice at the global scale and into the historical magnitudes of this transport.

The local scale (i.e., horizontal distances of kilometers or less) is where the climate system controls the exchange of volatiles amongst the atmosphere, surface, and subsurface. A number of science questions remain unanswered in this domain. For example, we lack extensive observations of the mechanisms that control the vertical movement (i.e., surface/atmosphere exchange, deposition, abrasion, sublimation, and mixing) of volatiles and dust from the surface to the boundary layer and then to the top of the atmosphere in both polar and non-polar regions. Our limited observations of near-surface winds, atmospheric turbulence, dust lifting, and sublimation/deposition processes have provided an incomplete picture of how diffusion and turbulence work to vertically transport volatiles both to and away from the surface. Similarly, these same limited observations only hint at the conditions that control the sublimation and deposition of water and CO_2 ice and at the conditions for transporting these volatiles into the subsurface. Without further investigation into these properties, a number of questions remain regarding dust and volatile activity at the poles, including *"What are the factors that control the current mass balance of the surface H_2O and CO_2 ices?"* and ***"What are rates of deposition and removal of ice and dust on the residual caps in the current climate?"*** (which are closely tied to questions in Priority Science Area D/§3.4).

Finally, the local-scale and global-scale transports are connected by the atmospheric radiative balance. An ongoing science question involves how much the frequently changing, small-scale atmospheric phenomena (e.g., water ice cloud formation, CO_2 ice cloud formation, dust lifting, and dust distribution) affect the atmospheric radiative balance. The atmospheric radiative balance controls the deposition and sublimation of water ice and CO_2 ice while also controlling the strength and structure of the global circulation. Yet, the sensitivity of the atmospheric circulation to small-scale phenomena remains an under-investigated area of Martian research. To improve our understanding of the relationship between the small-scale phenomena and the flux rates of volatiles, in future investigations we need to understand *"How is ice formed in both the atmosphere and at the surface, how are dust lifting and entrainment processes affected by the presence of ice, and what is the radiative response to the resultant combination of ice and dust?"*

3.1.1 Measurements to study the transport of volatiles and dust (A)

The Mars boundary layer is the interface through which heat, momentum, water vapor, and dust are exchanged with the surface and free atmosphere, where they influence global atmospheric circulation, and as a result, the planet's climate state. The transport of a property can be defined by its transfer through a given area in a given time, that is, as a flux. For example, the transport of thermal energy (resulting in heating or cooling, i.e., $\rho c_p Tv$) is quantified as the thermal energy of a unit parcel ($\rho c_p T$) transported by the wind (v) . We can quantify the movement of other properties in a similar manner. Therefore, to measure transport, we need to simultaneously measure the velocity and property (e.g., water vapor mixing ratio) of an air parcel. This is true at both the global and local scale.

From orbit, we can measure the meridional and zonal transport of volatiles and dust by measuring the wind velocities while also measuring water mixing ratio, dust concentration, and temperature, among other properties. These measurements should be made throughout the atmospheric column, sampling the atmosphere from the surface to the upper atmosphere with a vertical resolution of at least half the scale height (<~5 km). By measuring winds and other properties over all longitudes and, ideally, from all latitudes, we would be able to derive the time-varying transport of volatiles and dust.

Table 3.1. *Key questions within Priority Science Area A.* ***Bold = Highest priority.***

Q1	**How does the atmosphere control the exchange of ice and dust between ice reservoirs, within global-scale horizontal and vertical transport?**
Q2	How does the atmosphere control the exchange of ice and dust between ice reservoirs, within local-scale vertical transport?
Q3	Where are the dust sources and sinks, and how do these connect to the fluxes/distribution of lofted dust?
Q4	**What is the current annual net (global-scale) mass flux transport of volatiles, including H_2O and CO_2, and dust from/to polar and non-polar ice reservoirs?**
Q5	What are the factors that control the current mass balance of the surface H_2O and CO_2 ices?
Q6	**What are rates of deposition and removal of ice and dust on the residual caps in the current climate?**
Q7	How is ice formed in both the atmosphere and at the surface, how are dust lifting and entrainment processes affected by the presence of ice, and what is the radiative response to the resultant combination of ice and dust?

There are a number of ways to directly measure the atmospheric winds from orbit, including through the use of a submillimeter instrument or a Doppler LiDAR instrument. Previously flown instruments, like radiometric bolometers and infrared spectrometers and radiometers, have measured the atmospheric temperature, volatile mixing ratio, and dust abundance. Repeating these observations while simultaneously measuring the wind velocities would enable the direct measurement of transport in the atmosphere, while placing it in the context of the accumulating climatology. Alternatively, direct measurement of areopotential heights can yield indirect wind measurements; these can be obtained using radio occultations. Radio occultation observations have been done between a Mars orbiter and the Earth since the dawn of planetary exploration (e.g., Mariner 6 and 7 [Kliore et al., 1969], Viking [Fjeldbo et al., 1977], Mars Global Surveyor [Hinson et al., 1999; Noguchi et al., 2017], and MAVEN [Withers et al., 2018]), yielding much information about atmospheric structure. To get wind measurements, these types of observations should be done at much higher resolution and with greater coverage over the planet's surface; one way to accomplish this may be to use small satellites that occult one another frequently (§4.8).

Measurements from the surface would provide information about the near-surface and boundary layer transport of volatiles and dust. Measuring vertical profiles of wind velocities, volatile mixing ratios, dust concentration, and temperatures, among other properties, would illuminate the strength of vertical and convective mixing from the surface to the upper atmosphere. Ideally, these measurements would span the planetary boundary layer (approximately the lowest 10 km of the atmosphere) with sufficient vertical resolution while also measuring winds and other properties throughout the troposphere and into the upper atmosphere. An upward-looking Doppler LiDAR can provide vertical profiles of wind velocities, water vapor, dust, and aerosol concentration and composition. Other forms of LiDAR such as the one on the Phoenix lander, are capable of observing through the lowest ~20 km of the atmosphere with a resolution of 10s of meters [Whiteway et al., 2009]. Temperature profiles and some aerosol properties can be measured by upward looking radiometers and infrared spectrometers, among other measurement techniques. Bolometers can measure the downwelling IR and VIS radiative fluxes and reflected and emitted radiation from the surface. An upward looking mid-IR spectrometer can derive temperature and aerosol profiles in the atmospheric boundary layer. In concert with a comprehensive meteorological suite of instruments (see below), aerosol profiles would help determine dynamical mechanisms that loft ice and dust out of the planetary boundary layer and into the free atmosphere, where it can be transported globally.

A comprehensive meteorology station at the surface of Mars would provide valuable information about the near surface transport of volatiles and dust, both horizontally and between the atmosphere and the surface. Such a meteorology station should measure the winds near the surface with sufficient temporal resolution to resolve the three-dimensional turbulent eddies that are ultimately responsible for the exchange of momentum and material, including water vapor and dust, between the surface and the atmosphere. This station should also measure the net energy flux balance at the atmosphere-surface interface. The combination of these measurements would provide the observations we need to completely characterize the atmospheric-driven exchange of volatiles, dust, and energy between the surface and the atmosphere. A comprehensive meteorology station should include a three-dimensional anemometer, air temperature sensor, and water vapor mixing ratio sensor that measure the same volume of atmosphere at the same time, which would allow the measurements of eddy fluxes that can be correlated with the energy balance measurements. The net energy balance measurements can be acquired using radiometers, bolometers or spectrometers. Regardless of the technique, the rest of the sensors should have sample frequencies comparable to and in phase with each other, which would allow a complete analysis of the fluxes at the atmosphere-surface interface that control the transport and exchange of ice between the atmosphere and the surface. There are a number of different configurations of these instruments that are capable of providing the needed measurements.

To measure the turbulent eddies, the anemometer, air temperature sensor, and water vapor mixing ratio sensor must all be observing the same volume of atmosphere at the same time. The rest of the sensors should have sample frequencies comparable to each other, which would allow a complete analysis of the fluxes at the atmosphere-surface interface that control the transport and exchange of ice between the atmosphere and the subsurface.

Operation of the meteorology station for at least one Mars year would be required to understand the Mars energy budget at that location; measurements at multiple locations would provide an understanding of environmental variations. However, operation of one capable meteorological station over at least the sunlit portion of a year would greatly advance understanding over present knowledge.

A station that also contains instruments for concurrently measuring the local occurrence, mass flux, and frequency of sand saltation and/or dust entrainment (potentially caused by saltating sand) would enable direct determination of threshold wind conditions for these sediment transport processes. While some in situ observations of sand movement and concurrent wind measurements have occurred [Bridges et al., 2017], due to general instrument accommodation limitations and in flight damage to the *MSL* wind sensors, these measurements lack the accuracy and coverage to constrain models of wind-driven transport and erosion or help predict dominant sites of dust sources. Nearly any level of concurrent measurements that can robustly connect particulate movement to surface wind speeds would help constrain these models, but measurements over at least a full Mars year from at least one location are needed to monitor how the intensity of dust lifting changes with season, so as to more completely constrain the mechanisms behind dust lofting and surface abrasion.

Table 3.2. *Key measurements within Priority Science Area A.* ***Bold = Highest priority.***

M1	**Wind velocities, global-scale and including within boundary layer**
M2	**Water mixing ratio, dust concentration, temperature, and pressure, at a global-scale and including within boundary layer**
M3	Vertical profiles of wind velocities, near the surface and at high-spatial and temporal-resolution
M4	Vertical profiles of aerosol concentration and composition, near the surface and at high-spatial and temporal-resolution

ICE-SAG FINDING 3. Precise measurements of the transport of materials through the Martian atmosphere and between the atmosphere and surface/subsurface are key for determining how volatiles and refractory materials are moving into and out of the polar regions and how vertical structure forms within ice reservoirs. Simultaneous measurements of winds, the water mixing ratio (or absolute humidity), temperature, pressure, net radiation balance, and dust concentration, at the surface and within the atmospheric boundary layer, are crucial missing data that are needed to address these questions and to characterize the present climate.

3.2 Priority Science Area B: Global distribution and volume of subsurface ice

Subsurface ice has been detected in middle and high latitudes (§2.1.3), but the inventory of non-polar ice is not well constrained and such information is relevant to critical high-level questions about Mars' recent climate history. When the latitudes where subsurface ice is deposited shifts (due to e.g., obliquity changes), the latitudinal-boundary where near-surface ice is stable will migrate slowly with time as a function of temperature and atmospheric water vapor content. The depth to ice also will vary, sensitive to climate. As discussed in §2.1.3, direct evidence of ice in the shallow subsurface in the mid- and low-latitudes has not yet been found, particularly in the depth range ~1 to 10s of meters. Thus, answering the key question, ***"Where does subsurface ice presently exist, and at what depth?"*** would provide an indication of the integrated history of ice deposition and stability in recent times, and can tell us which areas should currently be undergoing sublimation or deposition if not sequestered.

Although subsurface ice is expected to occur primarily at mid- and high- latitudes, identifying low-latitude outliers would also provide important information about past climate conditions and mechanisms for preservation of ice. There are several possible sources for such anomalous ice. Most obviously, pole-facing slopes are colder than level ground, and thus there may be ice on such slopes at latitudes well below the nominal stability boundary; determining the stability boundary for ice on slopes would complement and cross-check information derived from the primary boundary, since deposition and removal rates should be different at those locations. Additionally, a variety of other low-latitude locales have been suggested to have out-of-equilibrium ice deposits or to have had ice in the recent past, and detections at such sites would provide important constraints on the recent history. Perhaps the most prominent of these is the Medusae Fossae

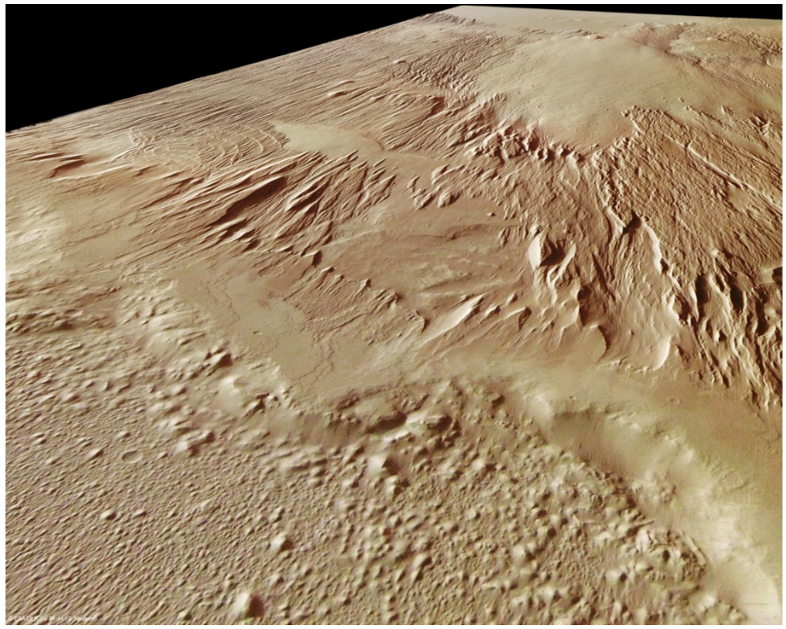


Figure 3.3. *The Medusae Fossae Formation is a vast, Hesperian sedimentary deposit near the equator of Mars. Its wind-eroded surface indicates that it is friable, and its low dielectric constant suggests it either ice-rich or very porous. Image credit: ESA/DLR/FU Berlin (G. Neukum).*

Formation (MFF; Fig. 3.3), which straddles the equator and has been the subject of recent debate [e.g., Carter et al., 2009; Ojha and Lewis, 2018; Watters et al., 2007].

To determine the total ice inventory, it is also necessary to answer, *"What is the volume and purity of water ice present in the non-polar ice reservoirs?"* Determining the thickness and purity of the subsurface ice is an essential complement to the spatial distribution and equilibrium conditions, as initially large volumes of ice can persist while out of equilibrium for extended periods, but thin shallow deposits should adjust more rapidly. Thick deposits also would require strong or protracted episodes of deposition to form. Additionally, a knowledge of the total ice inventory is essential to understanding the history of water migration in recent times and water loss over the complete history of Mars. Without knowing how much H_2O is available, we cannot accurately predict how various reservoirs would grow or shrink.

Advances in our understanding of the distribution of non-polar ice would also connect with other major questions discussed in this section. In particular, the fluxes of volatiles from unstable ice reservoirs would provide inputs about water vapor transport over regional and local scales (§3.1), and gaining a better understanding of the conditions under which ice may be stabilized could yield information to address the question of whether or not the PLDs and residual caps are presently stable (§3.1). Although this priority science area is focused on the bulk content and vertical structure of the ice reservoirs, detailed information about the volumetric ice content and vertical structure (§3.3) would also be of significance. For instance, where ice is present, has a high volumetric ice fraction, and is currently unstable, then ice loss landforms are likely currently active; under other conditions those landforms may be remnants of past conditions.

There also are many open questions relating to *"Which parts of the Martian surface have been or are currently formed or modified due to ice-driven processes?"* These questions sometimes connect to how liquid water may drive some of the surface evolution (§3.5). For instance, the relationship between polygonal landforms and where near-subsurface ice exists would help address whether these landforms are active today or are remnants of past/sublimed ice, and enable better interpretation of the significance of such morphologies. Mapping the distribution and thickness of ice would also illuminate the origins and nature of units such as mid-latitude mantling deposits, commonly thought to be atmospherically deposited ice/dust mixtures formed in the recent past, which have been proposed to generate melt that could drive gully formation.

A final high-priority question within this priority science area is "*Where is CO_2 ice present in the subsurface*?" This seems unlikely except at the very highest latitudes, where buried CO_2 deposits have been reported adjacent to the SPRC (§2.1.1). The full extent and depositional history of such ice remains to be determined, including if significant amounts of CO_2 are cycled between the atmosphere and ice reservoirs.

Table 3.3. *Key questions within Priority Science Area B.* **Bold = Highest priority.**

Q8	**Where does subsurface water ice presently exist, and at what depth?**
Q9	**What is the volume and purity of water ice present in the non-polar ice reservoirs?**
Q10	Which parts of the Martian surface have been or are currently formed or modified due to ice-driven processes?
Q11	Where is CO_2 ice present in the subsurface?

3.2.1 Measurements to study the distribution of subsurface ice reservoirs (B)

To address questions regarding the global distribution of ice, the basic requirement is high-resolution mapping of the structure within the top few 10s of meters of the Martian subsurface. It is desirable for this mapping to be conducted at considerably higher spatial resolution than the coarse data available from gamma-ray and neutron spectroscopy (GRS/NS), and sensitive to a greater depth. A horizontal pixel scale of 10–100 m would be comparable to global CTX and THEMIS data, allowing comparison to geomorphology and thermal data sets, and should be capable of resolving small ice outliers, such as the many pole-facing, few-hundred-meter scale slopes, which may harbor the most equatorial occurrences of ice.

Depth information is also valuable, both to the top of the ice table and to its base. Determining the depth to the top of the ice table provides information for stability models and data on the lag thicknesses that have accumulated over time, while determining the base provides volumetric information and insights into the total ice accumulation. Both theory and existing observations indicate that the depth to the top of the ice is a few centimeters to a few meters for normal ground ice, and may be up to 10 meters on debris-covered glaciers. The base of potential mid-latitude ice in Arcadia and Utopia Planitia has been measured to reach many tens of meters [Bramson et al., 2015; Stuurman et al., 2016]. Depths of tens of meters is likely at the 68°N Phoenix landing site [Putzig et al., 2014].

Numerous techniques can provide some insights into the ice distribution, including GRS/NS, thermal mapping, spectroscopy, geomorphology, and topography. However, the most effective way to achieve the desired coverage and resolution is with radar. Specifically, Polarimetric Synthetic Aperture Radar (PSAR) is capable of detecting ice with the needed spatial resolution, and a sounding radar with a higher frequency and bandwidth than SHARAD would provide constraints on the thicknesses of ice and overburden. As noted above, information on the vertical structure of the ice (especially depth from surface) and the near-surface atmospheric water vapor content would be highly complementary to the mapping of ice, and the effect of combining these data sets would be greater than the sum of the parts. Where ice begins at very shallow depths (< 1 m), GRS/NS and thermal instruments can provide some information about the depth to ice, so it is less important that a radar instrument be capable of resolving those depths.

Existing instruments can contribute to addressing these questions as well. Although SHARAD lacks the desired resolution and does not provide comprehensive spatial coverage, it can provide detections of ice and estimates of the ice thickness in many cases. HiRISE is capable of resolving many landforms thought to be related to ice, although it does not detect ice directly. Additionally, ice-exposing craters and icy scarps (commonly found with CTX or THEMIS data and followed up with HiRISE and CRISM) provide point measurements with information on ice presence, thickness, and depth-to-ice when visible in an outcrop. THEMIS observations can constrain models for the depth to ice where it is very shallow [e.g., Bandfield, 2007]. None of the current data sets can provide a global map with the necessary spatial and vertical coverage, but all of them provide complementary information that would be valuable for improving the interpretation of radar data [e.g., Morgan et al., 2019]. In addition, high-resolution topography models would be needed to remove clutter from high-frequency radar sounder observations.

Table 3.4. *Key measurements within Priority Science Area B.* ***Bold = Highest priority.***

M5	High-resolution, regional-to-global mapping of near-surface water content
M6	**High-resolution, regional-to-global mapping of near-surface structure**
M7	Near-surface atmospheric water vapor content
M8	Identification and characterization of ice-exposing craters and icy scarps
M9	Identification and characterization of landforms thought to be related to ice

ICE-SAG FINDING 4. Measurement of the spatial distribution and volume of non-polar subsurface ice deposits, along with the depth to ice, is key for determining the total volatile inventory on Mars, where ice may be stable in the present climate, and how it has been retained in locations where it is thought to be unstable. A primary need is the mapping at sub-meter-scale resolution of the near-subsurface within the uppermost 10 m.

3.3 Priority Science Area C: Vertical structure within ice reservoirs

The two polar layered deposits, high latitude ice-filled craters, and several smaller mid-latitude ice deposits are known to have vertical structure based on optical imagery of outcrops (e.g., Fig. 2.1). In the case of the PLD, subsurface radar interfaces may connect outcrops that are separated by hundreds of kilometers (Fig. 2.2), and so the layers are considered to be isochrons, or units that were deposited simultaneously over large areas. Similar to layered ice on Earth, the specific composition of a deposited Martian layer is thought to store information about the accumulation rate of volatiles and refractory materials and period over which they accumulated. The variable concentration of those materials in a vertical section, especially isotopes on both planets, and specifically dust for Mars, provides a detailed record of accumulation and thus climate through time.

Radar soundings and visible imaging of the PLDs have shown that there are thousands of layers within these ice reservoirs. Based on wavelet analysis, Fourier analysis, and unconformity mapping, "periodicities" within these layers have been tied to specific climate cycles [e.g., Becerra et al., 2017; Milkovich & Head, 2005; Smith et al., 2016]. Furthermore, some investigations have proposed that the NPRC is growing today [e.g., Brown et al., 2016; Vos et al., 2019]. If this is correct, at least in portions of the NPRC, then a new "layer" of frost (likely incorporating refractory materials) may be forming under present-day conditions and may eventually be preserved.

There are some indications of layering in mid-latitude ice deposits (Fig. 3.4) [Dundas et al., 2018], and some studies have suggested that these layers may preserve climate records [e.g., Schon et al., 2009; Dundas et al., 2018]. However, a clear vertical structure has not yet been mapped within these non-polar ice reservoirs, so no clear climate signals have yet been identified and thus hypotheses about climate cycles for the mid-latitudes have not yet been tested. The record in layers in these locations may be from periods that are out of phase with the PLD, as deposition at the poles and mid-latitudes likely occurs at different times. Layering in the mid-latitudes is not as contiguous as at the PLD, where individual layers/reflectors can be traced for ~1000 km [Phillips et al., 2008], and whereas some icy units have age estimates based on crater counting there is neither evidence to support an interpretation of present day accumulation nor a clear estimate for the age of the uppermost, highly modified layer.

Investigations of the general vertical structure of ice reservoirs, and in particular identification of extensive and "periodic" layers that may relate to a specific climate or climate shift, are needed to forward our understanding of what climate signal may be contained within these reservoirs. Measurements of the detailed layer structure and composition are needed to constrain *"What composes and defines a layer?"* and *"What is the thinnest observable layer?"* in both the PLDs and the mid-latitude ice reservoirs (the answers might be different). To enable interpretation of an individual layer, we also need to know ***"What are the physical, chemical, and isotopical nature of constituents that may be present in the layered ice on Mars, that reflect a climate record?"*** to determine how the volatile and refractory composition (and the ratio between them) may vary vertically in a way that was influenced by the climate at the time they were deposited (despite post-deposition modification). This question is especially important for the PLDs, where the connection between variations in the layers and a specific climate or climate shift has been more strongly hypothesized. Additionally, information about the structure and physical characteristics of the uppermost layers are of importance for future investigations as they can guide engineering design and instrument choice to access the subsurface, so as to extract additional climate information (or provide humans with in situ resources, §3.7).

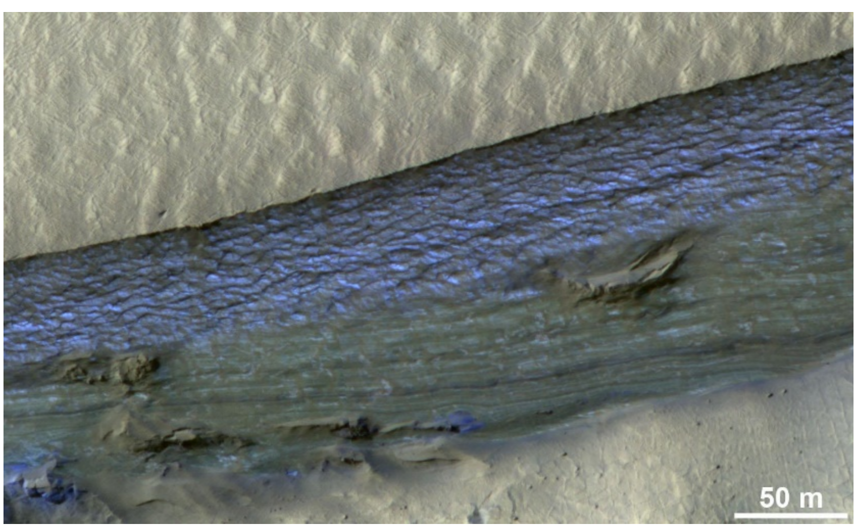


Figure 3.4. *Fine layers and a textural change in ice-rich material exposed in a steep scarp near 57°S (HiRISE enhanced-color image ESP_057321_1220).*

Table 3.5. *Key questions within Priority Science Area C.* ***Bold = Highest priority.***

Q12	What composes and defines a layer, in the PLDs?
Q13	What composes and defines a layer, in the mid-latitudes?
Q14	What is the thinnest observable layer, in the PLDs?
Q15	What is the thinnest observable layer, in the mid-latitudes?
Q16	**What are the physical, chemical, and isotopic nature of constituents that may be present in the layered ice on Mars, that reflect a climate record?**

3.3.1 Measurements to study the vertical structure of ice reservoirs (C)

There are multiple ways to interrogate the structure and composition of the layers, and in these methods there usually is a trade-off between depth of penetration and resolution. For example, in situ observations (e.g., acquired via drilling or exposed layers) could provide extremely detailed analysis of the structure and composition within individual layers, at sub-layer resolution. To measure layer properties over large areas, airborne or orbital instruments are likely required and these would yield bulk properties over a set of layers (e.g., a high bandwidth radar sounder may provide vertical resolution better than 1 m). In general, a depth of penetration >100 m in the PLDs is desired so as to capture obliquity shifts, but ~100 m penetration would be sufficient to map the spatial variability of NPLD accumulation for a period $>10^5$ years and to detect the bottom of mid-latitude deposits; ~10 m would be sufficient to determine the fine-structure of layers within the NPLD and mid-latitudes as well as the distribution of and depth to near-surface water ice reservoirs in the mid-latitudes; and ~1 m would be sufficient for an initial very high-resolution investigation of what composes a layer and how a layer may form and evolve. (For the last, if a lag is over the icy layers, the drill would need to go deeper.)

There are a few different techniques to remotely interrogate the subsurface structure, and it would be beneficial to employ more than one technique since each measures changes in a different subsurface property. TEM surveys use a conductive loop, meters in diameter, to induce an eddy current in the subsurface. The strength and decay of the measured eddy current is dependent on conductivity, and therefore sensitive to subsurface properties, and can pick up liquid water. Measured signals can be used to determine vertical variations in conductivity, down to tens to hundreds of meters, with the depth of sensitivity dependent on the size of the loop [Kneisel et al., 2008]. Dielectric Spectroscopy could provide ice detection using the relaxation of permittivity at low frequencies [Grimm and Stillman, 2015]. Ground Penetrating Radar (GPR) or Capacitively Coupled Resistivity Imaging (CCRI) [e.g., Wainstein et al., 2008] assesses subsurface structure by detecting changes in emissivity, thus detecting the boundaries of ice lenses or tables.

For a detailed investigation of the layers in a PLD, with an aim to connect such layers with formation processes (possibly ongoing today), it would be best to investigate the layers within the NPLD/NPRC since these units seem more clearly connected (in structure and composition) to each other, and possibly to present-day conditions and processes, than the layers within the southern cap (§2.1.1). For the detailed measurement of the composition and structure of layers within either mid-latitude ice or the PLD, investigations would be similar in scope to those used to characterize and date the layers within terrestrial ice cores. A vertical precision of at least 1 cm is desired for a drill that accesses the uppermost ~1 m of the vertical icy column, as this should access a substantial record and yet allow for characterization of and within specific layers. This depth is not sufficient to read Mars' climate record, but high fidelity measurements of at least the uppermost meter are critical to deepening our understanding of the processes that form and modify layers so that current layer-forming processes can be extrapolated backwards in time. (Further discussion about determination of current layer-forming process is detailed in §3.4.) Such a mission would provide important guidance for a future investigation to access a much longer (~100-1000 meter depth) icy column that would likely record the effects of obliquity shifts [Smith et al., 2018b].

Access to the layers could be achieved via several alternative platforms, such as a static lander with a vertical drill and sample handling (polar or non-polar ice); a rover that has instruments on an arm to traverse the exposed layers of the shallowly inclined spiral troughs (PLD only), or a rappelling vehicle on the steepest scarps (PLD or mid-latitude). In every case, the instrument suite should measure physical, chemical, and isotopic composition as a function of depth; micron-level analysis of ice-grain size and distribution of impurities; density and porosity with depth; thermal conductivity; electrical conductivity and permittivity; and temperature. Some specific quantities that would be important in supporting the interpretation of layers within an ice reservoir are:

- Percentages of dust (as nuclei for ice crystals or accumulating without ice), salts, and other lithic materials that comprise a few-% of the bulk volume of the PLDs and accumulate in variable ratios to the ice. Because most of Mars is covered by dust and some locations are activated at different surface pressures/wind speeds, variation in dust properties between and within an ice layer may both record climate conditions at the time that the layer was accumulating.
- Fractionation of isotopologues at phase transitions (solid-gas or gas-solid) may be of sufficient magnitude to leave a record of climate — including atmospheric species derived from various reservoirs of different ages and near surface temperature at the site of accumulation and sublimation. If this is similar to Earth, these may be the best way to extract chemical evidence of climate variability and determine absolute ages. Additionally, isotopic analysis of trapped gases in the ice would be of interest.
- Cosmogenic influences may also affect the materials that are deposited as ice accumulates; for example, ^{10}Be is known to vary within ice cores on Earth based on solar fluxes [Beer et al., 1991]. If present in sufficient amounts on Mars, the variability of its deposition in Martian ice may leave a history of Martian climate or age information at sites of accumulation.
- Many materials may arrive at the surface of ice-forming layers; however very little is known about how those materials integrate into the layers or if they can be modified post deposition. One obvious factor is the firn layer. On Earth, the firn layer, or the layer in which the ice has enough porosity to communicate with the atmosphere, may be tens to hundreds of meters thick. Several lines of evidence point against this for Mars, and the firn layer may only be a few tens of millimeters thick [Arthern et al., 2000]. If so, do buried layers communicate with the atmosphere at all? Do adsorption or diffusion play prominent roles in altering the layers after being cut off from communication?
- Additionally, within the ice matrix, chemical and physical forces will mobilize salts and other impurities to grain boundaries. The rate and magnitude of such mobilization is entirely unknown for martian ice, but they will have profound influences on our ability to extract climate signals.

Each of these properties will vary on daily, seasonal, inter-annual, and orbital change time scales, and it is likely that the forming layers record some of this variability. In particular, the finest resolvable layer may be formed through annual or multi-annual net accumulation.

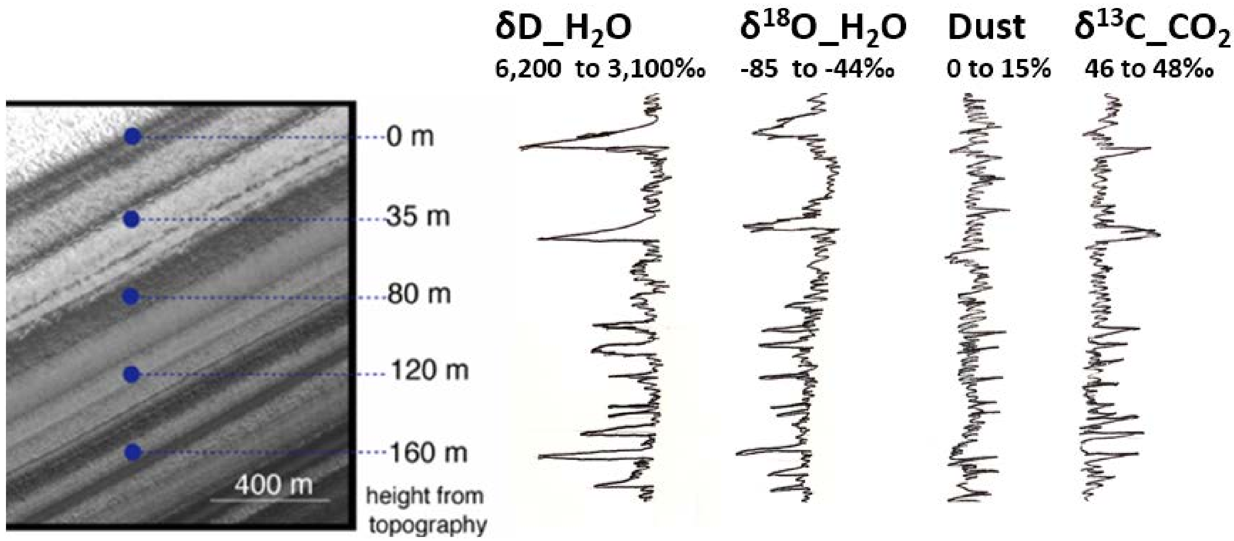


Figure 3.5. *Example of what the Martian recent climate record* <u>*may*</u> *look like, as reflected in physical, chemical, and isotopic constituents of the layers.* Left*: Stratigraphy of the NPLD captured by the MOC camera (image M00/02100 at 86.5°N, 80.5°E), converted to depth below the surface with MOLA topographic measurements.* Right: *a fictitious example of the measurements that we might see (generated by co-author Webster) in water and CO_2 isotopic data with dust, e.g., in an ice core sample through such layers.*

In order to make these measurements, several instruments would likely be required and some measurements may need to be made during drilling, in the borehole, or after samples have been delivered back to the spacecraft deck. For example, as part of the drill, material strength and density could be measured with drilling telemetry and ultrasonic velocity. Sensors for temperature and bulk electrical conductivity and permittivity could be part of the drill or lowered into the borehole later. To ascertain composition, a multispectral microscopic imager, Laser Induced Breakdown Spectroscopy (LIBS), or UV Raman could be used. Gases sublimed from the drill cuttings could be analyzed for species and isotopes with a Gas Chromatograph or Mass spectrometer. A tunable laser spectrometer could also be used to determine compositional and isotopic species. A micro-computed tomography (XCT) instrument would be useful for measuring the distribution of non-ice particles suspended in the ice matrix; in planetary science is commonly used to probe meteorites and returned samples [e.g., Hanna and Ketchum, 2017]. Use of this type of instrument may require extracting cores and non-destructive analysis prior to delivery to the other instruments. Finally, high-resolution imaging of the borehole would be needed to map and determine the depth/context of the fine layers that would be sampled.

Additionally, it is important to note that the specific concentration of refractory materials within a “layer” cannot be trivially related to ice accumulation rates when that layer was created. As orbital parameters, especially obliquity, change and the regions of net ice accumulation shift, newly exposed dust and other such lags will appear in regions of net erosion. Such lag material may be transported to other areas of Mars (perhaps to be captured within areas of ice accumulation), but some may be retained, creating a “layer” with a high-dust-to-ice ratio. Thus, interpretations of layers will also rely on models of global transport fluxes and lofting rates (§3.1), which may be changed under different orbital parameters and atmospheric conditions (§6.3). Additionally, an important consequence of dust and other materials within or atop ice that is not yet well understood is how they affect the evolution and stability of ice. Relating isotopic measurements in a layer (or a change in such measurements between layers) to specific accumulation rates will depend on models of isotopic fractionation processes. Finally, the record that is left behind does not immediately become locked and post-deposition atmospheric exchange can modify the initially deposited ratios, especially in the uppermost, forming layer, commonly called a firn layer (see §3.4 for further description). To address all of these complications, we must first know how much of what materials may be present within an ice layer.

In addition to the above measurements, high-resolution images and radar information about the layers would help connect characterization of a specific layer in a specific location to the general layered structure. Iteration is also needed between investigations incorporating process modeling, laboratory work, and in situ measurements so as to 'decode' the meaning of a specific layer's composition and structure, and connect the potentially large difference in timescales between annual (and decadal or centurial) processes and the formation of a "layer" in the ice.

Table 3.6. *Key measurements within Priority Science Area C.* ***Bold = Highest priority.***

M10	Subsurface structure down to 10(s) of meters, at meter-resolution, in the polar deposits
M11	Subsurface structure down to 10(s) of meters, at meter-resolution, in the mid-latitudes
M12	**Characterization of layered material (physical, chemical, isotopic, density, etc.), as a function of depth and correlated with specific layers, at centimeter-resolution and precision, in the polar deposits**
M13	Characterization of layered material (physical, chemical, isotopic, density, etc.), as a function of depth and correlated with specific layers, at centimeter-resolution and precision, in the mid latitudes
M14	Characterization of material (physical, chemical, isotopic, density, etc.) within exposed layers, at centimeter-resolution, in the polar deposits
M15	Characterization of material (physical, chemical, isotopic, density, etc.) within exposed layers, at centimeter-resolution, in the mid-latitudes

ICE-SAG FINDING 5. Mapping the structure and measuring the composition and properties of the layers within ice reservoirs is key for quantitatively determining the climate conditions throughout the record of climate history of Mars. Investigation of the vertical structure of the ice reservoirs can be done broadly via high-resolution orbital radar sounding, or locally via ground penetrating radar or drilling into the layers. The in-situ measurements enabled by drilling would yield characterization of fine layers that we expect to reflect the accumulation history of volatiles and refractory materials. A combination of these investigations, along with laboratory and modeling studies of processes, are needed to connect present-day observations and seasonal processes with the cumulative record of processes and conditions (including through climate shifts) in the layers.

3.4 Priority Science Area D: Formation conditions and processes for ice reservoir layers

To quantitatively correlate the stratigraphy seen in ice reservoirs with specific climate conditions (or climate shifts) at specific times, an understanding of the formative conditions and processes that lead to a "layer" is required. Of critical importance is investigating the current mass balance of the surface deposits of H_2O and CO_2. Of the stratified ice deposits on Mars, the SPLD and mid-latitude ices are expected to be stable in the present climate primarily because of protective layers that reduce sublimation in the present epoch, with formation happening under higher obliquity conditions [e.g., Mellon & Jakosky, 1995]. The NPLD is the only location on the planet where investigations have found that the ice may be accumulating in the present climate [Brown et al., 2016] and thus seems the better target for such investigations, although there is debate about that interpretation and the question about whether the residual caps are growing in the present climate remains open; nonetheless, we focus primarily on the NPLD in these questions and measurements..

As described under Priority Science Area A (§3.1), over both macro and meso-scales, it is still not known what factors control the mass balance over the residual caps. In addition to the atmospheric and radiative balance questions and measurements discussed previously, there are questions about *"How and how much frost is deposited on the surface?"* (including frost deposited via precipitation versus surface condensation) and *"How does seasonal frost evolve through the winter?"* (§2.4.2). Observations from orbit and the surface have tracked, at a coarse-spatial scale, the extent and timing of the seasonal frost layer [e.g., Piqueux et al., 2015] as well as identified some locations where snowfall may be a factor in ice deposition and layer formation [Hayne et al., 2014]. But a lack of detailed knowledge about what is happening at the surface through the polar night hampers efforts to connect processes to the formation of layers. Improving our understanding of the evolution of seasonal frost is important as the exact form of frost the forms through winter and that may be retained in spring may depend on specific environmental factors as well as "feedback effects" such as how the grainsize of the frost and dust-to-ice ratio will affect the frost's albedo, which will affect its internal heating and thus sublimation processes and rates.

In addition to estimates of frost amount and form, atmospheric fluxes of dust and water vapor through the frost formation and sublimation season are needed to constrain the frost formation environment and illuminate how dust, ice, and other materials will interact with other and affect surface accumulation of these different materials. Characterization of the surface wind environment is also important as winds are transporting materials (§3.1) and modifying the surface temperature. At the surface, measurements of volatile and refractory elements surface (through all Mars seasons) and existing layers are needed to address questions about what defines distinct layers (§3.3). Such measurements, along with monitoring of atmospheric and surface environmental conditions through all seasons, are needed to determine ***"What processes, including sublimation and deposition of ice and other materials, make and modify a layer?"*** All of these factors will affect the net annual accumulation of materials (affecting whether or not a new layer is being formed now) as well as modify near-surface ice that is heated and/or in communication with the atmosphere.

In summary, knowledge of the materials that arrive at the ice surface in different atmospheric and climatic states, combined with observations of how those materials are incorporated into the surface and then behave post-deposition are extremely important for understanding what makes a layer and if those layers are readable for future exploration.

Table 3.7. *Key questions within Priority Science Area D.* ***Bold = Highest priority.***

Q17	How and how much frost is deposited on the surface?
Q18	How does seasonal frost evolve through the winter?
Q19	**What processes, including sublimation and deposition of ice and other materials, make and modify a layer?**

3.4.1 Measurements to study the deposition of ice and formation of layers (D)

To understand the Martian recent climate record, both measurement of the vertical structure of the ice (§3.3.1) and observations that detail formation of the presently forming layers are critically important. Thus, we must observe the processes that are active today and distinguish which of those processes yield markers within the layers. Important processes will include any communication between the surface and atmosphere that involves transport of volatiles or other material. Due to the highly localized (in time and space) nature of some of these processes, in situ measurements are likely the only way to acquire needed information.

Because many of the processes happen during polar night or early in the spring, a mission capable of arriving during the sunlit portions of the year and acquiring in situ measurements throughout the winter would be immensely valuable (although challenging — e.g., §5.1, §5.2); minimally, observations of springtime frost and its sublimation and then early frost accumulation (ideally including both snowfall and surface condensation), coupled with laboratory and modeling studies of seasonal frost evolution (§6.1) would significantly advance our knowledge.

Above the surface, it will be important to measure the temperature, pressure, absolute humidity, large scale winds, and turbulent eddies. A competent meteorological station can measure all of these properties (described in §3.1.1). Additionally, an instrument that can distinguish between atmospheric components, such as a tunable laser spectrometer (T-LS), would be required. A T-LS similar in functionality to the Tunable Laser Spectrometer on board the *MSL* [Mahaffy et al., 2012] can make measurements of atmospheric isotopes, such as oxygen isotopes in H_2O and CO_2, and near-surface absolute humidity. Relative humidity is an insufficient metric of atmospheric vapor content for the purpose of assessing ice-layer formation because it approaches zero for long stretches of the day. It is preferred to have a measure of the absolute content (mixing ratio) of water vapor in the atmosphere in order to characterize temporal variations over the full diurnal cycle.

On the surface, measuring the accumulation rate of H_2O, CO_2, and refractory compounds is critical. The goal is to measure the bulk accumulation and ratio of dust and salt to ice as the seasonal frost forms. Methods to perform these analyses are varied, but the landed platform must have some way to measure the total mass of the accumulating materials and separate the volatiles from the non-volatiles. One instrument capable of these measurements is a high precision thermo-gravimeter that can cause the volatiles to sublime – getting the total mass and refractory mass of each accumulation period. It also will be important to estimate the relative contributions of snowfall versus surface condensation, to the seasonal frost layer.

Additionally, all of the types of measurements described in §3.3.1 for interrogation of the layers should be collected within the seasonally forming frost. In particular, to connect layers to present-day processes, it will be important to monitor the accumulation, crystal growth, density, and thermal properties of seasonal CO_2 throughout polar winter, as well as how and how much water ice and other materials are included. Then, repeat microscopic images of ice crystals and the surface matrix and repeat images of surface texture are required to observe evolution through spring and summer seasons. Changes in CO_2 ice grain size affect the albedo and structure of the frost layer [e.g., Eluszkiewicz, 1993; Matsuo & Heki, 2009]; and changes in retained water ice grain size may be a strong control on pore closure within surface ice [Arthern et al., 2000]. Such changes within the frost layer would thus have implications for radiative balance and sublimation activity in the spring, as well as the depth of firn ice and models of post-deposition evolution of layer structure and composition.

Table 3.8. *Key measurements within Priority Science Area D.* ***Bold = Highest priority.***

M16	**Meteorological conditions (i.e., surface temperature, pressure, absolute humidity, winds, etc.) above an icy layer, through a full Mars year**
M17	Accumulation rate of volatiles versus refractory materials onto the surface, through a full Mars year
M18	Landscape and micro-scale changes to surface (including seasonal frost evolution) through full Mars year
M19	Rates of frost accumulation via precipitation versus surface condensation

ICE-SAG FINDING 6. Identifying which ice reservoirs may be currently growing and determining how a layer forms are critical for enabling interpretation of the layers as records of past climate. Measurements of the annual deposition of frost and refractory materials, determination of how those materials are incorporated into the surface, and identification of what may be retained before the next winter cycle are necessary at both local and regional scales and over daily through annual cycles.

3.5 Priority Science Area E: Potential evidence of liquid water

The possibility of near-surface liquid water in the present climate or in geologically recent times is of great interest for three reasons. First, liquid water can have strong effects on the morphology and chemistry of the surface or shallow subsurface, and thus is important for identifying/constraining Martian geologic and geochemical processes. Second, such effects are also important determining the possible habitability of Mars. Third, identifying conclusive signs of past or present liquid water on Mars would imply that specific environmental and climatic conditions occurred. In particular, the sublimation of water ice as its temperature rises results in a latent heat flux that is difficult to overcome in the current climate [e.g., Ingersoll, 1970; Hecht, 2002], even if suitable pressure and temperature conditions are reached when ice is not present [e.g., Richardson and Mischna, 2005]. This issue is reduced for brines, which may be liquid at lower temperatures and evaporate more slowly. Consequently, understanding when, where, and how much liquid occurs on Mars is valuable both because of its direct effects on the surface and as evidence for climate conditions.

One set of questions relates to *"Which surface features may be formed or modified by the flow of relatively large amounts of liquid water?" RSL* have been proposed as locations of present-day seeping water or brine, and gullies have been suggested as sites of snowmelt and runoff within the last million years (Fig. 2.9). However, in both cases this role is debated; RSL have also been suggested to be granular flows, and gullies could have been carved by the CO_2 frost processes that are active today [Pilorget & Forget, 2016] (§2.4.3). Detailed questions follow from those high-level issues. It is straightforward to ask whether liquid is present in active RSL, and this question could be answered clearly by in situ observations. For gullies the path is less direct. There are no CO_2-frost driven flows on Earth and we have never observed one in action on Mars, nor have we observed the deposits resulting from such a flow up close. Our understanding of how such flows are initiated and mobilized is lacking; we do not know, for instance, how much frost is required. Consequently, it is difficult to extrapolate their role into the past, or to understand what observable differences exist between them and putative wet debris flows. Additionally, a better understanding of the link between gully activity and varying obliquity and orbital configurations is needed to understand those controls.

Other landforms have also been suggested to relate to liquid: for instance, mid-latitude scalloped depressions have variously been attributed to melting [e.g., Soare et al., 2008] or sublimation [e.g., Morgenstern et al., 2007], and a variety of lobate features have been proposed to relate to freeze-thaw processes [e.g., Gallagher et al., 2011]. To understand these assorted periglacial features, a detailed understanding of the ice table structure and the origins of the ice is needed. Observations of surface activity can also inform understanding of these features, but changes may be very slow.

Smaller volumes of liquid water can occur more readily than bulk melting, as thin films, via deliquescence, or via eutectic melts or brines. Films of unfrozen water occur at the ice surface or at ice-mineral interfaces even at temperatures well below freezing, and may contribute to processes like the growth of ice lenses. This process depends on the soil mineralogy and salt content. Through deliquescence, some salts are also capable of condensing water vapor into liquid at sub-freezing temperatures and low relative humidity that occur on Mars [Gough et al., 2011; 2016; Nuding et al., 2015] (Fig. 2.6). While both processes are likely to produce only limited volumes, they may have important effects on soil chemistry, ice table evolution, and the formation of duricrust. Understanding where and how much liquid they generate is essential to unraveling those effects, and points to a need to understand soil and ice table structure as well as the distribution and amounts of deliquescent salts.

Laboratory and modeling efforts may be valuable in the effort to understand liquid water over the next decade (see §6.2). Small-scale phenomena like deliquescence and thin films may be particularly amenable to such efforts to define the conditions under which liquid occurs and quantify the amounts that might be expected. Additionally, CO_2 fluidization and related phenomena are poorly understood at present and could benefit from additional experiments and

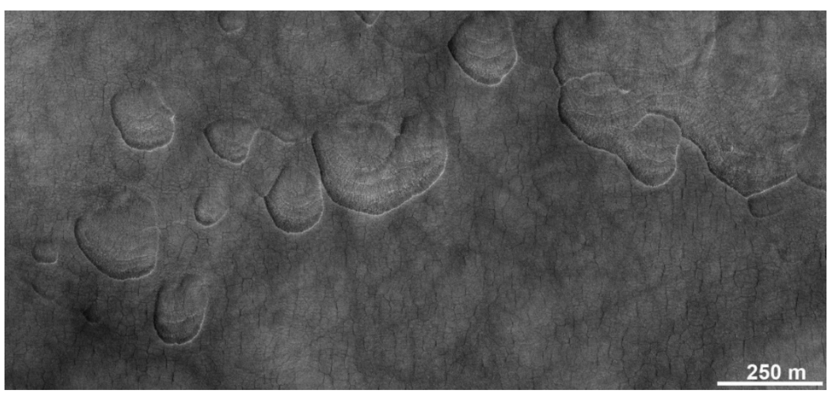


Figure 3.6. *Scalloped depressions in Utopia Planitia, showing characteristic steeper pole-facing slopes. These pits may be due to sublimation. The arcuate ridges on the pit floors may reflect climate variations. (HiRISE image PSP_008913_2255. North is up and illumination is from the left.)*

theoretical study to understand factors like fluidization that control the dynamics of such flows. Such work is needed to explain *"How do volatiles and volatile-driven processes cause Martian surface activity?"*

Table 3.9. *Key questions within Priority Science Area E.*

Q20	Which surface features may be formed or modified by the flow of relatively large amounts of liquid water?
Q21	How do volatiles and volatile-driven processes cause Martian surface activity?

3.5.1 Measurements to check for and interpret evidence of liquid water (E)

A variety of observations could help understand the possibility of current or recent liquid water on Mars. The strongest tests would be made in situ by directly looking for the effects of present-day liquid. Soil electrical conductivity or dielectric constant measurements could reveal the presence of small amounts of liquid water. Larger volumes might be obvious from simple imaging or excavation; near-infrared spectroscopy would provide a more definitive detection. The presence of liquid water should also strongly affect the thermal conductivity, and thus thermal inertia, of the wet soil [Edwards & Piqueux, 2016]. Additionally, measurements of the salt abundance and composition would improve models for the formation of liquid based on temperature and relative humidity information.

Landed imaging of flows in both RSL and gullies would shed light on the flow dynamics. At RSL sites, it would be possible to determine what triggers flows, how they behave over a complete diurnal cycle, and whether they behave like slowly seeping liquid or are dry. At gully sites, observations of the flow dynamics would help to understand the incorporation of CO_2 frost into the flows and consequent effects on flow behavior. This is directly relevant to understanding frost effects, but indirectly relevant to liquid water, as it would enable a better understanding of whether such flows operated in the past. In both cases, it would be most valuable to also learn the grain sizes and shapes involved, but coarser-scale (HiRISE-resolution) landed images with a high observation frequency would be sufficient to determine the flow velocity and initiation conditions. This should be coupled with observations of environmental conditions. For gullies the most important information is the amount, composition, and distribution of frost within the source area before and after a flow, while for RSL basic meteorological information (including temperature, water vapor mixing ratio, wind speed, and surface pressure) is needed to determine what conditions cause lineae to advance.

A number of periglacial landforms have tentatively been associated with liquid, but liquid-free models have also been proposed. For these landforms, the most valuable information would be observations of the state of the ice table (ice content and vertical/horizontal structure). Ideally these observations would be at very high resolution (much finer than landform scales of meters to hundreds of meters), but lower-resolution observations would still be of value. Additionally, observations of surface change could demonstrate that landforms are currently active and demonstrate the formative processes. Relevant scales of observable change range from multi-meter-scale changes detectable from orbit (e.g., gully flows) through thermal contraction cracking (millimeter to centimeter resolution required) to sub-mm-scale changes associated with slow sublimation of ice.

Current instruments can contribute to understanding the possibility of liquid water; e.g., *MSL* is gathering relevant meteorological information and soil-chemistry data within Gale [e.g., Gabriel et al., 2018; Martin-Torres et al., 2015]. Understanding whether landforms require liquid water is also inextricably linked with studies of surface changes. Continuing to characterize current activity to determine activity frequency and spatial extent is thus important to understanding the history of liquid water. Continued monitoring by HiRISE or an equivalent instrument is thus of very high value, as this combination of resolution, signal-to-noise ratio, and color coverage has proven invaluable in detecting changes (also highly prioritized in NEX-SAG [MEPAG, 2015]). Characterization of changes by CRISM or an equivalent instrument is also useful in identifying mineralogical compositions suggestive of the presence of past or present liquid water (or that would be inconsistent with the presence of water).

Table 3.10. *Key measurements within Priority Science Area E.* ***Bold = Highest priority.***

M20	High frequency and high resolution monitoring (from ground) of present-day activity and the local environment
M21	Catalog/survey of types and amounts of frost forming around Mars
M22	Continued monitoring of Martian surface to identify surface activity

ICE-SAG FINDING 7. A key open question remains regarding the possibility of mid- or low-latitude liquid water at or near the surface in the present or recent climate, despite many relevant studies. Laboratory and modeling work to better define conditions under which liquid occurs and to quantify the amounts expected to create observable chemical or geomorphological changes are needed. Results would guide future investigations, which may be based on both updated analysis of current Mars datasets and on new in situ or orbital observations of a potential liquid-water driven surface activity.

3.6 Relationship of Priority Science Areas to Astrobiology

In determining the recent climate history of Mars, important contextual information would be generated for any studies of past or present habitability, and identification of where to look for signs of extant or past life. For example, determining the global CO_2 volatile budget and how CO_2 may be sequestered as ice or significantly increase atmospheric pressure through obliquity cycles [e.g., Bierson et al., 2016] would answer recent climate questions, but also have implications for identifying past and present habitable zones due to effects on surface and subsurface warming [e.g., Richardson & Mischna, 2005; Wood et al., 2012]. As Priority Science Areas A–E each contain questions that would advance our understanding of the present and recent Martian climate, all thus have connections to astrobiology investigations.

Additionally, investigations of ice on Mars could have direct implications for the search for evidence of extant or past extraterrestrial life, and planetary protection. On Earth, microbes are now known to survive in a variety of settings associated with ice: from permanent Antarctic lake ice, glaciers, and ice sheets, to sub-glacial lakes [e.g., Priscu et al., 1999; Priscu and Christner, 2004]. They have also been reported from accretion ice under a 4-km-thick layer of glacial ice in Lake Vostok [D'Elia et al., 2008]. These types of microbes can live on the surfaces of glaciers and ice sheets where melting is occurring [e.g., Stibal et al., 2012] and in thin films of water on the surface of debris entrained in ice or in the network of veins that form between individual ice crystals. Price [2007] and Rhode and Price [2007] have reported that microbes can survive for more than 100,000 years inside of solid ice crystals deep in ice-sheets. Figure 3.7 shows one example of microbial life recovered from Subglacial Lake Whillans, which lies below ~800 m of ice in the Antarctic.

On Mars, current pressure, temperature, and humidity conditions are such that liquid water is not stable at the surface, and water ice is only stable at the poles). Nevertheless, ice on the polar caps and in the shallow subsurface may be an indicator of liquid water at depth, which may provide habitats for microbial life (i.e., a natural Special Region [Rummel et al., 2014]). Such life could exist (or have existed) within pore spaces and fractures of subsurface rocks (endolithic settings) and within thin films of liquid water associated with ice [Jakosky et al., 2004]. Such habitats could provide nutrients (from interactions between water and either minerals in rocks or dust entrained in ice. Rock matrices and ice may also provide a degree of shielding from DNA-damaging ultraviolet radiation [de Vera et al., 2019], and even localities distant from exposures of surface ice (e.g., RSL) could harbor such subsurface life. Morphological or geochemical remnants of past life that may have lived in such habitats (i.e., biosignatures) may be entrapped in ice that may have formed as the Martian climate cooled [Christner et al., 2003; Westall et al., 2015; Hays et al., 2017]. (Additional past or presently habitable regions may also be identified, after advancement within Priority Science Area E/§3.5.) It is also possible that ancient life that may have existed in a relatively clement, early Mars could have evolved to tolerate nutrient-limited endolithic habitats as well as habitats that became colder with time (though the lack of continuously hospitable conditions might have limited this possibility [Westall et al., 2015]).

Because of the potential analogies to terrestrial psychrophilic/psychrotolerant microbiotas and

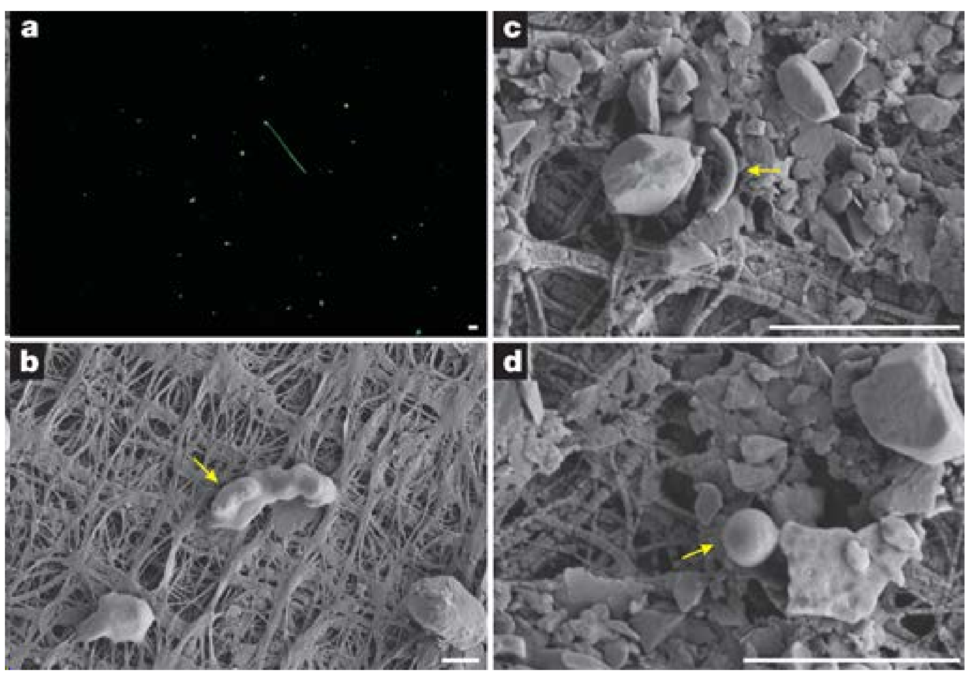


Figure 3.7. *Examples of terrestrial life in ice environments. Microbial cells in Subglacial Lake Whillans. (**a**) Epifluorescence micrograph showing a variety of cell morphotypes, which was confirmed by scanning electron microscopy (SEM; **b**–**d**). The yellow arrows in the SEM images indicate cells with rod (**b**), curved rod (**c**) and coccoid (**d**) morphologies. Scale bar, 2 μm. Water samples collected by hot-water drilling using microbiologically clean drilling and sampling techniques. (image approval provided by B.C. Christner, from Christner et al., 2014; permission to use provided by author and Springer Nature).*

possibilities that extant life on Mars might be associated with present day ice as described above, future missions involving ice-rich environments may include astrobiology investigations [e.g., Eigenbrode et al., 2019] and should consider the need to prevent contamination of the Martian environment by terrestrial organisms (forward contamination) as well as backward contamination of Earth by potential extraterrestrial life or bioactive molecules in returned samples. In considering forward contamination, this will be a significant concern for astrobiological investigations or landing at a natural Special Region anywhere on Mars, or when combined with potential creation of an induced Special Region [Rummel et al., 2014] within the mid-latitudes, due to spacecraft heating (§5.2).

ICE-SAG FINDING 8. Science investigations of ice and climate on Mars would yield important insight into environments that may be or may have been habitable. Additionally, for investigations that involve direct contact with ice reservoirs, there may be synergies with the search for evidence of extant or past extraterrestrial life and planetary protection concerns.

3.7 Relationship of Priority Science Areas to Human Exploration Interests

Beyond their science motivation, many of the investigations focused on by ICE-SAG are also highly relevant to future human exploration. The relationship between the Priority Science Areas identified above and human missions is multifaceted and relates directly to both in situ resource utilization (ISRU) and hazard identification. The prospect of transporting humans to the Martian surface also raises additional challenges relating to planetary protection. Indeed, efforts to exploit in situ resources would place humans within sensitive regions of high habitability potential, exacerbating the risk of terrestrial contamination of Mars. Some of the scientific investigations discussed within Priority Science Areas A–E would, therefore, be essential to negotiating the fine line between planetary protection-compliant scientific exploration, responsible ISRU activities, and the success of future human missions to Mars. The following paragraphs discuss ISRU and human hazards in turn.

The majority of mission architecture suggested to place humans on Mars anticipates the use of Martian H_2O deposits. Water is of course an essential component for life support systems, but as a source of oxygen and hydrogen, it also offers valuable fuel resources for surface operations and the return trip back to Earth. In terms of ISRU, the distribution and properties of water ice (and any liquid water) reservoirs are of the greatest consequence, rather than the processes and associated fluxes responsible for the deposition of ice. Knowledge of the ice reservoirs in terms of their location (both spatially and vertically), volume, volumetric ratio of ice to non-ice (i.e., contaminants), and vertical structure (especially around the top of the ice table) will be essential to mission design and planning, and thus Priority Science Areas B/§3.2 and C/§3.3 are of greatest relevance. Should a type of landform be clearly connected to present-day liquid water (Priority Science Area E/§3.5), that could also have large import for the identification of accessible water. To-date, there has been much interest from those designing potential human exploration systems in geomorphological and radar-based evidence for large water ice reservoirs within the mid-latitudes [e.g., Morgan et al., 2019]. This work also relies heavily on laboratory and terrestrial analog investigations that enable better interpretation of radar and other remote detection of ice, such as accurately constraining the relationship between composition of ice layers and radar reflections (§6.1, §6.4). (An alternative approach is to harvest water from hydrated minerals or regolith containing adsorbed water, and this would be advanced by laboratory studies of water transfer through and interaction with regolith (§6.2).)

Ensuring mission success also requires a full quantification of the risks associated with landing and operating on the surface of Mars. During the Apollo program, the unexpected abrasive qualities of lunar dust were identified as a serious hazard to equipment and respiratory health. Mars has no shortage of dust, and the dynamic nature of the dust deposits in the Martian atmosphere relative to the vacuum of the Moon pose additional risks in terms of hindering visibility and preventing solar power generation. The chemical composition of the dust and other regolith constituents is another health risk. For example, perchlorates identified at the Phoenix landing site indicate toxicity of Martian soil. Windborne aerosols could carry terrestrial contaminants into regions of astrobiological interest, or bring toxins into areas explored by astronauts. Priority Science Area A is therefore of most relevance to risk assessment, and Priority Science Area D could also yield information regarding dust grain characteristics and the fluxes and transport distances of dust around Mars.

A comprehensive understanding of these interactions requires surface measurements of atmospheric properties, the need for which was identified in white papers prior to the 2013-2022 Planetary Science Decadal Survey [Mischna et al., 2009; Rafkin et al., 2009], and which are discussed in the MEPAG Goals Document [MEPAG, 2018], within Goal II, Sub-objective A1. Thus, investigations of surface-atmosphere interactions that yield answers to climate and ice science-related questions (§3.1) would also address questions of interest to planetary protection and human exploration. For example, NASA's Office of Planetary Protection (OPP) and Human Exploration and Operations Directorate (HEOMD) recognize that preventing contamination of the Martian environment by terrestrial organisms from humans operating on the surface (i.e., forward contamination) requires an understanding of near-surface winds and dust entrainment [Johnson et al., 2016; Spry et al., 2017].

ICE-SAG FINDING 9. Measurements addressing high-priority Mars ice- and climate-science investigations have major implications for in situ human exploration. In particular, detection and characterization of near-surface ice reservoirs is of keen interest for potential in situ resource utilization, although human proximity to ice-rich locales has implications for planetary protection. Additionally, many high-priority surface and atmospheric measurements would yield important inputs for understanding the hazards associated with dust and other windborne risks.

3.8 Tracing to MEPAG Goals

Every Priority Science Area in this document contributes towards, and often directly maps to, a MEPAG goal, objective, sub-objective, or investigation [MEPAG, 2018]. Table 3.1 shows the connections between our focus areas and the 2018 MEPAG Goals, to the Sub-objective level; Appendix D quotes the specific relevant MEPAG Goals, to the Investigation level.

Unsurprisingly, ICE-SAG's Priority Science Areas connect most strongly with the MEPAG Climate and Geology-focused Goals (Goals II and III). In fact, some questions posed in our Priority Science Areas correspond very directly to key questions posted in the MEPAG Goals document, such as:

- The first Objective in the Climate Goal focuses on understanding the present state of and active processes within Mars' atmosphere, including specific focuses on the lower atmosphere and surface-atmosphere exchange of volatiles and dust (Goal II, Sub-objectives A1 and A4). Additionally, the second Objective focuses on the history of Mars' climate in the recent past (Goal II, Objective B).

- The Climate and Geology Goals contain several Sub-objectives related to identifying and interpreting signs of present or past water on Mars, including identifying subsurface water ice reservoirs (Goal II, Investigation B3.1; Goal III, Investigation A4.3) or their effects on surface features (Goal III, Investigation A1.4). Also included in the Climate Goal is understanding how subsurface ice reservoirs persist to the present, and to determine their ages (Goal II, Investigation B3.2).
- The Geology Goal also contains a Sub-objective focused on understanding present-day activity, which relates to connecting the present-climate to observable landforms and changes (Goal III, Sub-objective A3 and Investigation A4.2).
- Questions about dust transport are also included in the Geology Goal (Goal III, Investigation A1.6).

Beyond connections to the Climate and Geology Goals, there are also connections to the Life and Preparation for Human Exploration Goals (I and IV) with regards to constraining past or present habitability and finding potential water sources; as discussed in §3.6 and §3.7, investigations of Mars' present and past climate, and its ice reservoirs, have strong connections to both astrobiological and human exploration interests.

ICE-SAG FINDING 10. Key measurements addressing high-priority science questions relevant to ICE-SAG and the 2018 MEPAG Goals would yield substantial advances to our understanding of recent Mars climate history and resource potential of Martian ice.

Table 3.11. *Traceability between the ICE-SAG Priority Science Areas and the 2018 MEPAG Goals. Clear connections are noted, as well as less direct or weaker connections (italicized).*

	2018 MEPAG Goals > **v ICE-SAG High-priority science questions**	**I Life**	**II Climate**	**III Geology**	**IV Humans**
(Overarching) What is Mars' recent climate history?		B1	A	A	*contributes to B3, D1*
(A) Transport of volatiles and dust into and out of ice reservoirs					
Q1	**How does the atmosphere control the exchange of ice and dust between ice reservoirs, within global-scale horizontal and vertical transport?**		A4	A3, A1	*contributes to A1, B1*
Q2	How does the atmosphere control the exchange of ice and dust between ice reservoirs, within local-scale vertical transport?		A1, B3	A3, A4	
Q3	Where are the dust sources and sinks, and how do these connect to the fluxes/distribution of lofted dust?		A1, A4	A1	
Q4	**What is the current annual net (global-scale) mass flux transport of volatiles, including H_2O and CO_2, and dust from/to polar and non-polar ice reservoirs?**		A1, A4	A1	
Q5	What are the factors that control the current mass balance of the surface H_2O and CO_2 ices?		A4; *feeds into B2*	A3, A4	
Q6	**What are rates of deposition and removal of ice and dust on the residual caps in the current climate?**		A4; *feeds into B2 & C3*	A3, A4	
Q7	How is ice formed in both the atmosphere and at the surface, how are dust lifting and entrainment processes affected by in the presence of ice, and what is the radiative response to the resultant combination of ice and dust?		A4	A1	
(B) Global distribution and volume of subsurface ice					
Q8	**Where does subsurface water ice presently exist, and at what depth?**		B3	A4	B3, D1
Q9	**What is the volume and purity of water ice present in the non-polar ice reservoirs?**		B3	A4	*contributes to B5, feeds into D1*
Q10	Which parts of the Martian surface have been or are currently formed or modified due to ice-driven processes?			A1, A3, A4	
Q11	Where is CO_2 ice present in the subsurface?		B1		
(C) Vertical structure within ice reservoirs					
Q12	What composes and defines a layer, in the PLDs?		B2		
Q13	What composes and defines a layer, in the mid-latitudes?		B3		*feeds into D1*

Q14	What is the thinnest observable layer, in the PLDs?		B2		
Q15	What is the thinnest observable layer, in the mid-latitudes?		B3		
Q16	**What are the physical, chemical, and isotopic nature of constituents that may be present in the layered ice on Mars, that reflect a climate record?**		B1, B2, B3		
(D) Formation conditions and processes for ice reservoir layers					
Q17	How and how much frost is deposited on the surface?		A1, A4	A3; *feeds into A1*	
Q18	How does seasonal frost evolve through the winter?		A1, A4	A3; *feeds into A1*	
Q19	**What processes, including sublimation and deposition of ice and other materials, make and modify a layer?**		A4	A1, A4	
(E) Evidence of potential liquid water					
Q20	Which surface features may be formed or modified by the flow of relatively large amounts of liquid water?	B1, B2; *feeds into A1*		A1	
Q21	How do volatiles and volatile-driven processes cause Martian surface activity?	B1, B2		A1, A3	

4 Mission Concepts to Address Key Ice and Climate Science Questions

ICE-SAG discussed many mission concepts that could address key questions over a broad range of mission sizes. In this report, we put our primary focus on mission concepts that could conceivably fit within NASA's New Frontiers (NF) class (costs of approximately $850M in FY18 dollars). All of the larger mission concepts we considered were effectively those in the NF-class with more capability, whereas most of the smaller mission concepts we discussed were effectively descoped NF-class concepts. Here, we first describe our five NF-class concepts (some with alternative implementations, so more than five individual mission concepts are included), and within each description, we note ways to expand or contract the concept to fit other mission classes. We then discuss a few additional concepts that we believe could fit within Discovery class ($500M in FY19 dollars) or smaller mission classes.

These mission concepts are intended to be illustrative of what might be achieved during the next decade, within a range of cost-classes, to address key science questions (§3) and do not constitute a restrictive set of possible mission concepts or sets of measurement types or techniques. As will be discussed in this section, ICE-SAG finds the following:

ICE-SAG FINDING 11. Compelling, high-priority Mars ice- and climate-science questions are addressable by mission concepts that are feasible within the next decade. These mission concepts span a range of mission-sizes/classes, and architectures.

ICE-SAG FINDING 12. Five mission concepts larger than the NASA Discovery-class have been identified that would address high-priority Mars ice- and climate-science questions. These concepts appear feasible in the next decade but have remaining technological and costing questions. A detailed costing and technology development study of these mission concepts, or other concepts aimed at achieving similar measurements, would address these questions and contribute important information to a discussion of compelling potential Mars missions in the next decade.

ICE-SAG FINDING 13. Smaller mission concepts (i.e., Discovery-class or "small spacecraft") could address subsets of the high-priority ice- and climate-science questions, while still making notable and worthy advancement on our understanding of the recent Martian climate.

We note that our estimates of cost[4] and technology development for these concepts are very rough, being based heavily on analogy with existing or heritage instruments and missions. A few concepts were planned out in slightly greater detail, via support from the Mars Program Office and JPL's Team X (see *Supplemental Materials*), and these concepts are described first (§4.1–4.4). However, even for these, the cost model used was very simple and many factors were considered at only a high-level (e.g., spacecraft accommodation); a more careful estimation of cost for e.g.,

[4] *The cost information contained in this document and in the Supplemental Materials is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.*

the payload after considering accommodation on the spacecraft, would be needed for a robust cost estimate.

The ordering of the mission concepts described and the choice to explore some of them in greater detail with Team X are not intended to represent a prioritization of the concepts. The ordering also is not intended to reflect a suggested timing of the missions, and there is no identified rationale for carrying out any of these concepts in a particular order. (Nevertheless, the mid-latitude lander concepts (§4.4) could benefit from a precursor orbital ice-mapping mission (§4.5). The benefit is probably greatest for the multiple-lander concept, where there is a desire to land on both ice-rich and ice-free sites, spanning the transition region.) We also note that each mission concept would meaningfully address a subset of the high-priority questions and measurements needed to investigate Mars' climate history (a summary of this is presented in this report's Conclusion (§7, in Tables 7.1 and 7.2).

> **ICE-SAG FINDING 14.** Each mission concept presented addresses a different subset of the key Mars ice- and climate-science questions. Certain aspects of these concepts could benefit from running some missions concurrently or in a certain order. For example, carrying out the orbiter concepts first could facilitate choosing sites for the landed ones, although such reconnaissance could instead rely upon current data or data being acquired by the ongoing missions at Mars. However, there are no explicit interdependencies between the concepts and each one could in principle be carried out independently of the others. Each mission concept would contribute meaningfully to high-priority Mars ice and climate science.

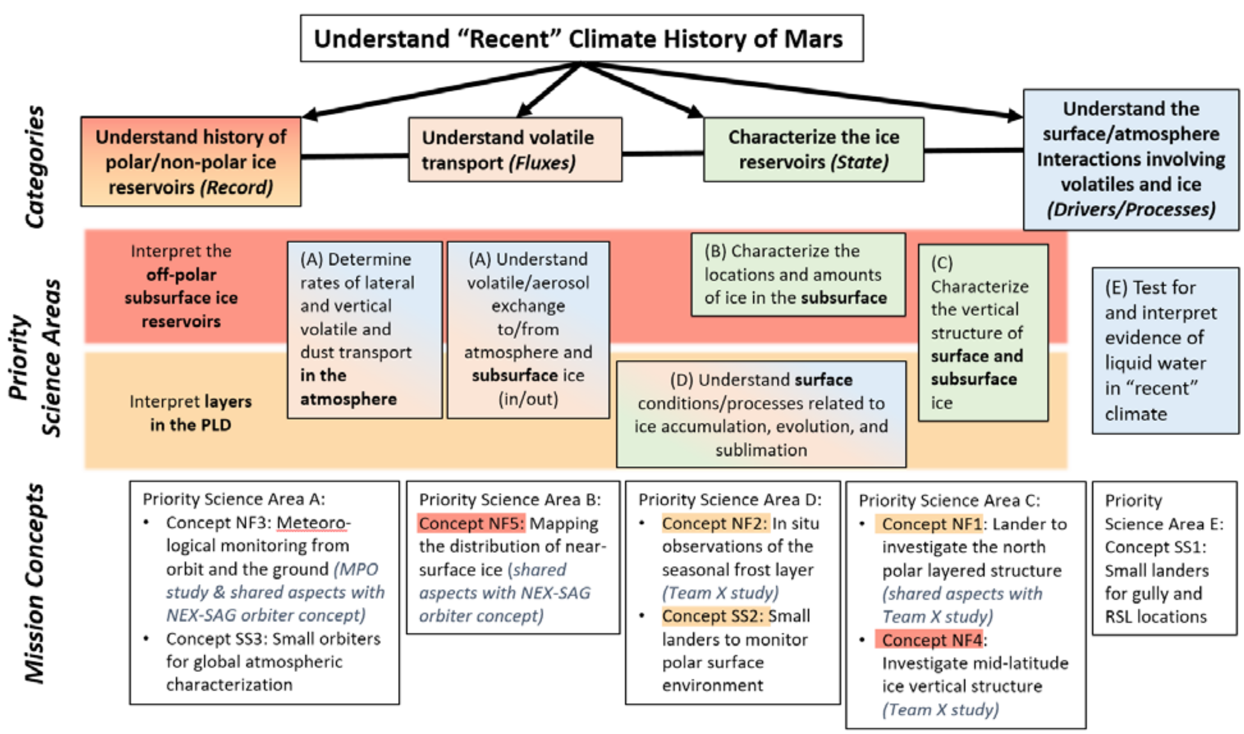


Figure 4.1. *Figure showing flow from Categories and Priority Science Areas science questions into the Mission Concepts described in this report. Upper portion is same as Figure 3.1. Concepts are described below.*

4.1 Concept NF1: Lander to investigate the detailed structure of the north polar layers and their present environment

4.1.1. Concept Overview

As described in §2.1.1, the NPLD is thought to be essentially a stack of past NPRC-type deposits, each of which interacted with the climate at the time it was at the surface. Thus, to fully 'decode' the climate record contained within the NPLD, we need to understand both how the NPRC interacts with today's climate and the properties of NPLD layers (past NPRC deposits). The mission concept presented here would study, in situ, both present-day Mars climate conditions at the NPRC surface and NPLD stratigraphy, and thus:

- Determine the record within the uppermost part of the NPLD. This may be accomplished by drilling and detailed analysis of the uppermost meter or using a ground-penetrating radar (GPR: §3.3.1) to characterize the upper 100s of meters or both. (It is anticipated that simultaneously pursuing both of these approaches would be outside the scope of a New Frontiers mission.) In both cases, detailed examination of surface ices is required.
- Determine what climatic information is recorded in a polar layer by quantifying the interaction of the current climate with the upper meter of the NPRC. The accumulation of 1 m is expected to take ~2 kyr [Hvidberg et al., 2012], and so the contents of the uppermost meter would be representative of the current climate, without influence of substantial changes in orbital elements. Year-round meteorology is required to quantify this surface-climate interaction.

Fulfillment of these goals would provide essential ground truth for orbital missions that study global climate as well as those that study the NPRC and the NPLD interior stratigraphy using more-deeply-penetrating (but lower-resolution) radar.

4.1.2. Science Questions Addressed

This mission concept would address questions in four ICE-SAG Priority Science Areas:

- **Meteorology and volatile exchange at the surface (A/§3.1)**
- **Vertical structure within ice reservoirs (C/§3.3)**
- **Formation conditions and processes for ice reservoir layers (D/§3.4)**

A detailed description of the science questions addressed by this mission concept are in Table 4.1, along with tracing from these questions to measurements and instrument-types for acquiring the measurements.

Drilling and conducting GPR investigations of the upper section of the NPLD would determine the vertical structure of the most recently deposited polar ice, i.e., that which is linked to the most recent climate. Current datasets do not provide this information. SHARAD does not resolve layers that are closer together than ~8.4 m [Putzig et al., 2009] or within ~15 m of the surface [Putzig et al., 2014]. High-resolution images of trough exposures are limited due to a pervasive sublimation lag [Herkenhoff et al., 2007] that obscures thin layers.

A major gap in our understanding is how layer properties reflect the climate during their formation. It's clear that climate and NPLD layer properties are changing through time, but the climatic interpretation of these properties remains elusive. By conducting a detailed analysis of surface materials and meteorological conditions at the surface over a full year, this concept would link current climate with current ice properties and provide needed information for interpreting the longer stratigraphic record.

4.1.3. Measurements and Conceptual Instrument Suite

Year-round meteorology (including during polar night) is required to address a key scientific goal of this mission concept. The required measurements could be achieved by:

- A **Meteorological station** to measure temperatures, pressures and humidity, including a **Differential Absorption LiDAR (DiAL)** to characterize the vertical distribution of water vapor and precipitation and a **Sonic Anemometer** to quantify near-surface winds and eddy fluxes (§3.1.1)
- A **Tunable Laser Spectrometer (T-LS)** to characterize near-surface water vapor and isotopic ratios (§3.4.1)
- **Bolometers** to measure downwelling IR and VIS radiative fluxes and reflected and emitted radiation from the surface (§3.1.1)
- A **Thermogravimeter** to separately measure frost mass condensed and dust deposited
- **Surface cameras** to image the lander surroundings in stereo and monitor changes over the spring and summer

Another key goal of this mission concept involves the investigation of subsurface ice layers. Two ways to accomplish the subsurface investigations would be drilling or GPR:

- A 0.5–1 m **drill** could pneumatically deliver samples at ~5 cm intervals (§5.5) to analysis instruments, listed below. A fiber-optic rotary joint and borehole microscopic imager allows in-situ characterization of subsurface composition, porosity, and layering at sub-cm resolution.

Samples of the subsurface may be analyzed by:

  - A **microscopic imager** to examine surface microtexture, dust contamination and porosity.
  - A **T-LS** to measure ice isotopes (§3.3.1, Fig. 3.5)
  - A **near-IR Raman spectrometer** to measure abundances of salts, silicates and oxides
  - An **APXS** to measure bulk chemistry
  - A **TECP** to measure the thermal conductivity and bulk density/porosity via the high frequency permittivity

- Alternatively, a rover with a **GPR receiver** (and minimal other instrumentation) could traverse up to 1 km from the main lander, where a GPR source is located. Performing several GPR measurements along this traverse allows the detection of subsurface layers and the assignment of a dielectric constant to each layer (Fig 4.2, §3.3.1). From discussion at the 2018 KISS workshop focused on Martian north polar science [Smith et al., 2018b], it was thought that such a rover could perhaps be intermediate in size, between Sojourner (Fig. 4.2) and the MER rovers (note the ICE-SAG engineering study assumed a larger rover: §4.1.4).

4.1.4. Key Technical or Science Challenges

Choosing a landing site at the NPRC is relatively simple as the NPRC is one of the smoothest locations at MOLA scales [Aharonson et al., 2001] (§2.1.1), has no large rocks (as it formed from atmospherically deposited ice), and the homogeneity of the NPRC means that precision landing is not required. Additionally, its elevations (-4000 to -2000 m) are comparable to or lower than those

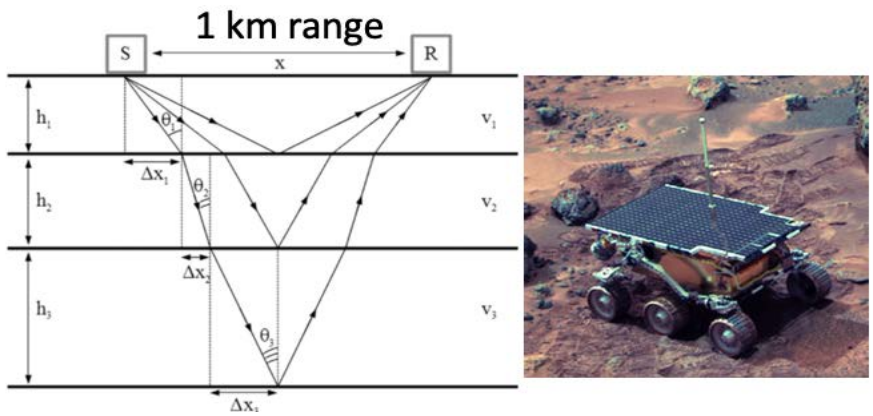


Figure 4.2. Left: *Schematic of how a separated radar source and receiver can discern subsurface layers.* Right: *The 66-cm-long Mars Pathfinder Sojourner as an example of the potential scale of a GPR-receiver rover.*

of other recent landing sites, so previously-used landing methods are feasible (note: the Team X study considered MER and Phoenix-EDL systems (Supplementary Materials); both MER- or Phoenix-scale landing ellipses fit entirely within the NPRC boundaries (Fig. 2.3)). However, there are limitations for some launch and propulsion setups (§5.4) on access to the poles during specific times of year, and there are some questions about how the descent radar may operate over the icy layers, depending on how porosity changes with depth.

A larger concern is that the landing system (and operations) would need to minimize chemical, mechanical, and thermal disturbances of the surface and environment around the lander, as the science goals of the mission require minimal physical and chemical alteration of NPRC materials adjacent to the lander (§5.3). During operations, there is also a risk that thermal waste could destabilize the surface under the lander.

At this latitude, energy-intensive summer activities would benefit from constant solar power. The thermal environment in this location is also extremely stable albeit cold. However, the polar night extends through half of the Martian year, and survival and data collection through the polar night would be a challenge (§5.1).

Additionally, the proposed use of a small rover to carry GPR would need further development. Fitting such a rover with the lander may also be an issue - in the Team X study of the mid-latitude lander, they assumed a small Axel-style rover (~1 m long, thus much larger than *Pathfinder*) coupled with an InSight-type lander as a starting design point and this likely necessitated an increase in lander/aeroshell size (Supplementary Materials). Questions were also raised about the power needs of the rover, should it be used for bistatic radar investigations with a range of up to 1 km. Further technology design for both achievement of the science objectives and accommodation would be needed.

If, alternatively, a drill was used to access the subsurface at the lander site, then much development work is needed for the drilling process, sampling mechanisms, and observation/measurement strategy (§5.5); such designs could be guided by experience with analogous terrestrial drilling (§6.4).

4.1.5. Alternative Implementations

The baseline mission concept described above lasts through the polar winter and either drills to 1 m or has a GPR-receiver rover that traverses 1 km. The threshold mission would:

- Last only throughout the summer
- *If with a rover*, reduce the rover's range to 100 meters

- *If with a drill,* remove the APXS, TECP and Thermogravimeter experiments.

An alternative mission architecture would trade the detailed layer measurements made by the concepts described above to enhance the spatial extend over which layer measurements could be made. The NPLD contains numerous low relief scarps that expose 100s to 1000 m of vertical section. These outcrops expose a cross section of the layering that defines much of the vertical structure of the polar cap. Because of the very low relief over the NPLD [Aharonson et al., 2001; Pathare et al., 2005], the scarps may be traversable by a rover. At the outcrop level, roving through the stratigraphic column would provide an unprecedented view of the stratigraphy of the NPLD, at resolutions orders of magnitude better than current orbital observations (e.g., Fig. 2.1).

Transferring all (or a subset) of the lander instrumentation to the rover would enable the high-resolution interrogation of the composition, structure, and vertical diversity of the layers of the NPLD, and thus would answer the question of what constitutes a layer. Additionally, comparing the stratigraphic layering sequence observed by the rover would provide further constraints with which to interpret the GPR data. Access to individual layers within a scarp is likely to be hindered by surface lag a few cm thick. Thus, a Rock Abrasion Tool (RAT) similar to that used on MER would be required to access the pristine deposits of interest. Additionally, instruments capable of analyzing the exposed material could be included in the rover arm (e.g., Raman, wet chemistry, IR and UV spectroscopy, and LIBS).

If surviving the winter is feasible, introducing a more capable rover would also enable the actively forming layer (and the near surface environment) both at the landing site, and at multiple locations within the surrounding region, to be assessed. Multi-site measurements of the layer forming processes would identify any significant spatial variations that could reflect the importance of localized surface/atmospheric conditions.

Table 4.1. *Science tracing to notional payload for Concept NF1: Lander to investigate detailed structure/composition of NPLD*

Science Question	Measurements	Instrument Type and Purpose
How do the current climate and surface of the polar deposits interact? *From Priority Science Area A/§3.1:* Q2: How does the atmosphere control the exchange of ice and dust between ice reservoirs, within local-scale vertical transport? **Q6: What are rates of deposition and removal of ice and dust on the residual caps in the current climate?** Q7: How is ice formed in both the atmosphere and at the surface, how are dust lifting and entrainment processes affected by the presence of ice, and what is the radiative response to the resultant combination of ice and dust? *From Priority Science Area D/§3.4:* Q17: How and how much frost is deposited on the surface? Q18: How does seasonal frost evolve through the winter? **Q19: What processes, including sublimation and deposition of ice and other materials, make and modify a layer?**	A. Determine the mass balance of surface water ice B. Determine the dust deposition rate	(A) Sonic Anemometer: Characterizes turbulent eddies and wind speeds (A) T-LS: Characterizes near-surface vapor concentration (A + B) DiAL: Characterizes the vertical distribution of water vapor and atmospheric dust, as well as any water precipitation (B) Thermogravimeter: Characterizes the precipitation rate of dust
	A. Determine surface frost properties and its spatial heterogeneity	(A) Color Stereo Camera: Tracks surface frost distribution through the frosted seasons
	A. Determine the radiative forcing of the surface	(A) Bolometers: Characterizes the downwelling VIS and IR flux
What is the nature of the recent NPLD climate record? *From Priority Science Area C/§3.3:* Q12: What composes and defines a layer, in the PLDs? **Q16: What are the physical, chemical, and isotopic nature of constituents that may be present in the layered ice on Mars, that reflect a climate record?**	A. Determine the physical state of NPLD material as a function of depth B. Determine the presence of cosmogenic isotopes and their precursor atoms as a function of depth C. Determine the chemical composition of NPLD material as a function of depth D. Determine the stable isotope record as a function	(A) Drill: Characterizes mechanical strength and retrieves subsurface samples (A) Drill/Microscopic Imager/TECP: Characterizes porosity (A) Drill/Microscopic Imager/Raman: Characterizes dust/ice ratio (A) Drill/TECP: Characterizes thermal conductivity (B) Drill/APXS: Characterizes bulk elemental chemistry

	of depth	(C) Drill/Near-IR Raman: Characterizes the abundances of salts, silicates and oxides (C) Drill/Near-IR Raman/Wet Chemistry: Characterizes soluble species abundances (D) Drill/T-LS: Characterizes C, O and H isotopes
How are near-surface layers connected to the deeper stratigraphic record? *From Priority Science Area C/§3.3:* Q12 Q14: What is the thinnest observable layer, in the PLDs?	A. Determine the stratigraphy at sufficient resolution to resolve layers sampled by drilling and sufficient depth to overlap orbital radar.	(A) GPR with separated source and receiver: Characterizes radar reflections at cm-scale down to decameters in depth

4.2 Concept NF2: In situ observations of the seasonal frost layer, as it evolves

4.2.1. Concept Overview

Polar layer deposits keep a record of past Martian climate evolution through preservation of layers of ice and dust deposited under varying climatic conditions. This record can be decoded to understand what Martian climates looked like in the past. However, the decoding process relies on an in-depth understanding of the processes involved in the layer formation, i.e. transport of volatiles and dust to and from the poles and their accumulation at and removal from the surface. Understanding these processes are important inputs towards connecting annual accumulation to the cumulative record of the icy layers. One way to develop and refine models of these processes is to develop robust models of present-day processes that may be acting on the surface of the PLDs, potentially creating a new record of the present climate.

The main scientific goal of this mission concept is to understand the present-day processes by observing the climate conditions and seasonal evolution of the surface icy deposits in the polar regions through one complete Martian year. This mission concept aims to land on the NPLD to monitor seasonal frosts through the complete cycle of their deposition and sublimation and to contemporaneously characterize current weather and climate conditions in the polar regions, specifically in the polar boundary layer.

To avoid initial burial under seasonal frost, the lander would arrive in early spring on top of the seasonal CO_2 ice layer, at latitude ~80°N or higher. Northern hemisphere and high latitude were chosen because of their representative environmental conditions for layer formation. The lander would monitor the sublimation of CO_2 and water ices in spring, and into the summer and fall, as far as possible into the polar night. The most important scientific return would be achieved if the lander is able to operate through the complete Martian year, making observations of the seasonal frost layer as it accumulates and evolves in the polar night. Survival through multiple Mars years would also be of interest, so as to observe interannual variations in the seasonal cycles. However, detailed observations of sublimation/condensation conditions and fluxes of volatiles and dust in the polar regions through a portion of the Mars year (i.e., spring through early fall) would be an extremely valuable scientific return as this is a key knowledge gap within models of present-day Martian volatile and seasonal cycles.

4.2.2. Science Questions Addressed

As of today, our understanding of the processes that form seasonal ice layers is overwhelmingly derived from climate models that are based on limited remote-sensing data as inputs and validation. For example, over all of Mars, limited measurements of surface and atmospheric temperatures are used in combination with surface topography within models of atmospheric fluxes to predict wind patterns. Very little direct wind data exists to check these models, and mesoscale wind models are generally poorly connected to expected surface wind conditions [e.g., Newman et al., 2017]. A similarly poor connection between surface conditions and global circulation is found within measurements of water vapor. Polar regions are disadvantaged in the scheme of climate modeling because the polar regions are in permanent darkness during polar nights, and thus no passive visible remote-sensing instrument is able to do measurements. Morphological and compositional analysis thus has to rely on indirect measurements (such as surface temperature). However, the activity and environmental changes that are occurring during the winter include the conditions and processes that may form a layer.

In situ measurements from a mission that can survive and observe through the polar night season would provide invaluable ground-truth data, leading to a significant advance in our understanding of the local and global transport of volatiles, and generally of the processes that happens within the atmosphere and surface through the polar night (relating to **Priority Science Area A/§3.1**). Such measurements would inform us on how and how much volatiles and dust may be retained within the PLD through a season, forming an annual record and eventually accumulating into a layer (**Priority Science Area D/§3.4**). With such observations, we might begin to quantitatively interpret the vertical structure seen within various ice reservoirs, and interpret the climate history of Mars.

The specific questions addressed by this mission concept are listed in Table 4.2. Additionally, correlating the results of monitoring the local weather conditions and monitoring the surrounding landscape would contribute towards answering: *What atmospheric or climate cycle is represented by the smallest physical layer of the PLD? What processes can be recorded in a single PLD layer and what are the signals of these records? What atmospheric processes (mechanisms) control the deposition and removal of water ice on the PLD?*

4.2.3. Measurements and Conceptual Instrument Suite

Measurements required to answer the above-mentioned scientific questions naturally fall into two categories: *a)* characterize the atmospheric state in the polar regions above seasonal ice layer through one complete Martian year, and *b)* monitor changes to the surface in the immediate surroundings of the lander. As we desire to establish connections between the constantly changing atmospheric state and surface variations in the ice layer, the simultaneous data collection by a set of instruments is required. Table 4.2 summarizes the required measurements in more details, and connects them to a notional payload.

This payload would consist of instruments to monitor the surrounding atmospheric and ambient environment:

- Meteorology station with temperature, pressure, and humidity sensors, including atmospheric LiDAR, looking up for clouds and winds monitoring (§3.1.1)
- Visible camera to watch the sky and landscape
- Bolometer to estimate the surface radiance (§3.1.1)
- Tunable laser spectrometer to look at atmosphere oxygen isotopes in H_2O and CO_2 (§3.4.1)

Instruments are also needed to determine frost properties and accumulation rates:

- Microscope (VIS, NIR) to look closely at surface – to measure ice and dust grain sizes, and evaluate composition
- Thermogravimeter or quartz-crystal microbalance to determine frost/dust surface accumulation rates and what is accumulating/changing

4.2.4. Key Technical or Science Challenges

This mission concept faces multiple technical challenges. The current concept involves landing in the high northern latitudes (80°N) on the seasonal ice layer after it has stopped accumulating but preferably before it completely sublimes. There are limitations on which launch opportunities have access to the high latitudes during early spring, for certain launch and propulsion setups (§5.4).

Minimal disturbance of the surroundings during landing is preferred (§5.3) and the survival of the lander through spring sublimation of the ice without tipping, and then continued stability on the icy surface, is required for the successful mission.

Following the summer observational campaign, the lander is also required to last into the local fall and as long as possible into the polar night (§5.1). The observations must be conducted with minimal disturbance of the surroundings through the lifetime of the mission, and both chemical and thermal perturbations are a concern (§5.3). However, there may also be a need to minimize frost accumulation on parts of the lander, so some heating relative to the environment may be necessary.

Finally, relay of the acquired data has not previously been done under the conditions of the Martian polar night when it may be challenging to retain sufficient power to transmit data from the lander and with seasonal frost forming on/around the antennae.

4.2.5. Alternative Implementations

To mitigate the risks involved with landing on the active seasonal ice layer and during a season with more sunlight, the landing could be performed in summer; however, that would remove the ability to monitor the frost environment during the spring and increase risk of losing frost-observations if the lander does not survive far into the subsequent autumn.

To mitigate contamination concerns for the environment - including those caused by chemical contamination during landing or thermal perturbations of the spacecraft, it may be necessary to move instruments away from the main spacecraft, such as via an arm/boom or a small tethered rover.

Table 4.2. *Science tracing to notional payload for Concept NF2: In situ observations of the seasonal frost layer*

Science questions	**Measurements**	**Instrument type**
What does the boundary layer atmospheric state look like in the polar regions at diurnal, seasonal, and annual time scales? How does this boundary layer state affect the vertical and horizontal thermal structure (including surface temperature?) and atmospheric circulation over the poles, and flux of volatiles and dust materials? *From Priority Science Area A/§3.1:* Q2: How does the atmosphere control the exchange of ice and dust between ice reservoirs, within local-scale vertical transport? **Q6: What are rates of deposition and removal of ice and dust on the residual caps in the current climate?**	A. surface pressure, temperature, humidity of the atmosphere directly above the lander B. presence/characteristics of aerosols and clouds, atmosphere composition C. wind speeds D. dust fluxes E. D/H in vapor	(A) Meteorology station with temperature, pressure, and humidity sensors (B+C+D) Atmospheric LiDAR, looking up for clouds and winds monitoring (B+D) Visible camera to monitor the sky and changes in atmospheric opacity (E) T-LS to look at atmosphere oxygen isotopes in H_2O and CO_2
Over a year, is mass currently being lost or gained from NPRC? What are the properties and behavior of CO_2 and H_2O frosts under the range of diurnally, seasonally, and climatically varying environmental conditions found on Mars? *From Priority Science Area A/§3.1:* **Q6** Q7: How is ice formed in both the atmosphere and at the surface, how are dust lifting and entrainment processes affected by the presence of ice, and what is the radiative response to the resultant combination of ice and dust? *From Priority Science Area D/§3.4:* Q17: How and how much frost is deposited on the surface? Q18: How does seasonal frost evolve through the winter? **Q19: What processes, including sublimation and deposition of ice and other materials, make and modify a layer?**	A. variations in surrounding surface albedo and its morphology and topography B. radiative flux from the surfaces C. amount and density/porosity/grain size of surface frost and atmospheric snowfall D. D/H in frost E. amount and grain size of deposited dust	(A+B+C) Visible camera to monitor the landscape, and a bolometer to estimate the surface radiance (C+E) Microscope (VIS, NIR) to look closely at surface – to measure ice and dust grain sizes, and evaluate composition (C+E) Thermogravimeter or quartz-crystal microbalance to determine frost/dust surface accumulation rates and what is accumulating/changing (E) T-LS to look at surface oxygen isotopes in H_2O and CO_2

4.3 Concept NF3: Investigation of present-day meteorology from orbit and the ground

4.3.1. Concept Overview

To address the goals of understanding ice and climate evolution, this mission concept is focused on a comprehensive assessment of the Martian water cycle, including first efforts to quantify the surface flux of water vapor, and the global, 4-D transport of vapor, ice, and dust over the Martian year. The new and novel measurements of global wind fields, vertical water vapor distribution, and surface vapor and dust fluxes require observations from both orbit and ground, along with supporting observations from instruments on both platforms.

As envisioned, the orbiter component of the concept consists of a payload to chiefly measure vertical profiles of wind, water vapor, and temperature, together designed to track the movement of water vapor, dust and water ice across the planet over the Mars year. To obtain information on multiple timescales, the orbiter would have a two-stage, evolving orbital mission design using solar-electric propulsion (SEP) technology to enable migration of the orbital inclination. The first stage would place the spacecraft in a Sun-synchronous, polar orbit, which would obtain atmospheric profiles at two fixed times of day over 12-13 daily orbits. The polar orbit ensures good coverage of both poles.

After one full Mars year, the orbit would be designed to shift to a highly inclined (but sub-polar) orbit. With this inclination, the orbiter observations would 'walk' in time of day, covering the full diurnal cycle with regularity, though at the expense of the loss of high latitude observations over one pole (due to the notional orientation of the orbiter instrumentation). The purpose of this shift in orbit is to view the diurnal evolution of water vapor in the atmosphere, particularly vis-à-vis the thermal and aerosol (both dust and water ice) structure with which it interacts. The baseline mission concept would maintain this inclined orbit for another Mars year but, with healthy instrumentation, could remain in this orbit indefinitely, extending our observational record of the Martian atmosphere, or, utilizing SEP, change to yet another orbit (this was a proposed use of SEP in NEX-SAG [MEPAG, 2015]). One Mars year in each orbital configuration, plus time to allow the spacecraft to shift between configurations defines the baseline orbital mission (as was described in NEX-SAG [MEPAG, 2015]). Given the significant interannual repeatability of Martian seasonal weather, this new dataset, and especially observations over the full day, can then be integrated into existing data, forming a fuller picture of atmospheric circulation.

A baseline, comprehensive landed meteorology station, such as that defined in §3.1.1, would address many of the science questions to be addressed by this mission concept (§4.3.2 and Table 4.3). At minimum, such a payload must include the ability to measure temperature and surface pressure, and obtain high frequency wind and vapor fluxes. Coincident measurements of vapor and wind should be of a high enough frequency to provide information about the surface flux of water vapor, which is a key unknown component of the water cycle. Additionally, they should provide sufficient measurements to link near-surface eddy motions (the local scale) to the larger-scale mean circulation (the global scale). Measurement of the flux of water into and out of the surface provides unique data about the diurnal behavior of the water cycle. Information about surface dust lifting and entrainment into the atmospheric boundary layer are also key elements to be obtained by the landed payload. While multiple lander locations, both on and off the polar caps, would be desirable, it is likely not feasible under the New Frontiers cost cap; hence, a single lander, on a non-polar surface with subsurface ice deposits in communication with the atmosphere, is envisioned as making the most significant scientific advancements.

4.3.2. Science Questions Addressed

Key science questions addressed by the joint orbiter/lander concept focus on global atmospheric circulation, and the role of the circulation on the transport of water vapor, CO_2 and dust (**Priority Science Area A/§3.1**). Together, these three interconnected atmospheric constituents control the distribution of water ice on the Martian surface, both on annual and multi-annual timescales. For example, movement of water vapor controls the stability of subsurface ice reservoirs. Formation of layers in polar deposits reflects varying levels of dust entrainment in the surface ice. The seasonal collapse/inflation of the Martian CO_2 atmosphere drives circulation patterns and regulates the water cycle through cold-trapping of water ice where CO_2 frost is found. At present, we have little in the way of quantitative measurements of the global atmospheric circulation—only numerical simulations of uncertain validity. Observing the three-dimensional wind field in conjunction with the three-dimensional distribution of water vapor, dust, and ice in the atmosphere would enable us to address the key science question: *What is the current annual net (global-scale) transport of volatiles, including H_2O and CO_2, and dust from/to polar and non-polar ice reservoirs?*

The north polar cap of Mars is the primary source of water in the Martian system. During northern spring and summer, sublimation of surface water ice leads to atmospheric mixing in the boundary layer, and subsequent transport, vertically, into the overlying free atmosphere. The global circulation, which has been numerically modeled and follows a similar structure to the Hadley circulation on Earth, then carries this water out of the polar region, to lower latitudes, and into the southern hemisphere. The cycle reverses during northern autumn and winter; however, the timing, depth and variability of this circulation has yet to be quantified by direct observation. Three-dimensional sounding of the atmosphere, especially in the polar and sub-polar regions, along with coincident surface measurements would enable us to address the key science question: *What controls the vertical movement (i.e., surface/atmosphere exchange, deposition, abrasion, sublimation, and mixing) of volatiles and dust from the boundary layer to the top of the atmosphere in both polar and non-polar regions with ice deposits?*

The proposed two-stage orbital mission design would enable useful measurements on multiple timescales from diurnal to interannual. From polar orbit, we can obtain measurements of the profiles of water ice, water vapor and dust in the polar regions, along with temperature, providing new measurements with regular, daily observations. The relatively slow transport of water vapor by the mean circulation can be adequately observed with a daily observational cadence. Comparing results from polar orbit with those from prior missions provides information about multi-annual evolution of the water cycle, and additional information about the interplay of atmospheric dust, water vapor and cloud ice. From a time-walking inclined orbit, we can acquire information about the diurnal variability of the water and dust cycles. For example, it has been observed [Heavens et al., 2014] that the depth of atmospheric dust changes rapidly from day to night. If, during this process, the dust is able to act as condensation nuclei for atmospheric vapor, then nighttime clouds may form, which may be observed, and which will impact the thermal structure of the atmosphere. The details of this time-varying behavior cannot be observed with current approaches, but present an important control on the speed of the overall vapor transport. The proposed mission concept provides a unique accounting of both water vapor and ice—the near total amount of water in the atmosphere—and allows us to address the key science question: *How do diurnal, seasonal, and multi-annual atmospheric cycles affect and/or control the distribution of ice in the atmosphere and on the surface?*

Global atmospheric circulation is driven by imbalances in heating of the atmosphere. These imbalances may derive from different levels of insolation due to geometrical considerations (latitude), surface properties (surface albedo) or atmospheric composition (dust loading, cloud distribution). This final consideration is the most challenging to effectively observe, because such features are typically transient and small, but may play an oversized role in modifying the net energy balance of the atmosphere. It is therefore essential to capture the growth and evolution of these clouds to properly characterize the atmospheric circulation. Instrumentation on both orbiter and lander, designed specifically to observe atmospheric aerosols, permits us to address the key science question: *To what extent do frequently changing, small scale features (e.g., water ice clouds, CO_2 clouds, dust distribution) affect the atmospheric radiative balance?*

4.3.3. Measurements and Conceptual Instrument Suite

The key orbital measurements needed to address the science questions above include globally sampled vertical profiles of water vapor and wind between ~10-80 km. A proof-of-concept instrument package that would satisfy these measurements would consist of the following:

Primary instrument:

- A **sub-mm atmospheric sounder** for obtaining 3-D wind and water vapor fields through the lower and middle atmosphere. The instrument is capable of observing day or night, and within both clear and dusty conditions, permitting a mapping of winds responsible for volatile or dust transport in nearly all conditions. This instrument can observe winds from near the top of the boundary layer (~10 km) to 80+ km altitude and temperature and water vapor from within the boundary layer to at least 80 km altitude, at <~5 km vertical resolution, meeting the sampling requirements outlined in §3.1.1.

Complementary instruments:

- A **thermal infrared sounder** primarily for obtaining vertical temperature profiles, surface pressure, and atmospheric aerosol (water ice and dust) profiles, with complementary water vapor measurements as well. The measurement approach is to observe the atmosphere in either a nadir or limb viewing orientation using multiple spectral filters to permit vertical profiling of the atmosphere. Different spectral bands are more/less sensitive to different atmospheric constituents. This instrument is capable of observing day and night across most of the planet.
- A **Doppler LiDAR** instrument capable of determining aerosol/cloud height, and wind speed/direction in more opaque conditions. The LiDAR operates best below 35 km where aerosols are most abundant. This instrument would be able to provide high-resolution profiles (2 km or better) both dayside and nightside, and is particularly suited to measuring winds in the boundary layer [Abshire et al., 2018]. However, very low or very high dust conditions would compromise these measurements.
- A **synoptic weather camera** with resolution on the order of 1 km/px for daily mapping of atmospheric behavior, including dust sources and cloud distribution, and tracking of the size of the residual polar caps over the course of multiple years. Such a camera would need a field of view sufficient to observe the poles regardless of orbital inclination, as well as obtain full global daily coverage of the entire planet. The camera provides context for other instruments on the payload, tracking short-term motion of dust and water-ice clouds and seasonal growth and recession of polar ice.

Wind measurements can be obtained by either the sub-mm sounder or Doppler LiDAR, but as noted above, the sub-mm sounder is selected as the primary orbital instrument in this conceptual mission due to its capability to measure both in the lower atmosphere and also higher in the atmosphere (e.g., near the core of the jet stream) allowing a fuller picture of the global circulation. The Doppler LiDAR has advantages which augment the payload, such as the ability to measure winds with higher resolution deeper into the atmosphere than a sub-mm sounder. Some of this may be recovered by instruments on the landed platform, however. Further, other techniques have been suggested and are being developed to measure winds such as infrared limb imaging and cloud tracking [Tamppari et al., 2018].

The core lander measurements needed to address these same science questions include surface pressure, surface and air temperature, high-frequency wind and absolute humidity to quantify the near-surface atmospheric circulation, along with measurements of dust lifting and entrainment, and aerosol/cloud height and atmospheric temperature profiles through the boundary layer. Most, if not all, of these measurements can be obtained by a capable, comprehensive meteorology station such as defined in §3.1.1.

4.3.4. Key Technical or Science Challenges

Many components of the proposed orbital payload use instrumentation that has relatively mature technology readiness levels, and several payload instruments have previously flown at Mars. The novel aspect of the orbital payload is certainly the instrumentation to measure atmospheric wind at Mars. However, the techniques themselves are not new, and have been demonstrated previously. For the sub-mm, it is believed that there are few major technical or scientific challenges associated with the orbital component that cannot be overcome with standard testing and design. Engineering challenges associated with minimizing the large power draw of the Doppler LiDAR concept are under development and continued instrument development may mitigate these concerns. SEP at Mars has yet to be demonstrated, but the propulsion technology itself is not new and has been flown in other interplanetary missions like Dawn [Brophy, 2011].

The lander payload is comprised of instrumentation that has flown previously on one or more missions. Most instruments are sufficiently small and low power so as to not require additional development for accommodation on multiple landers, even if they are smaller than those flown on previous missions. As with the orbital component of this concept, there may be engineering challenges associated with the large power draw of the Doppler LiDAR.

Perhaps the key scientific challenge is in demonstrating that a single lander, in conjunction with an orbiter can provide a substantial step forward in our understanding of the Martian atmosphere and, more specifically, the water cycle. Certainly, additional landed payloads, at different latitudes, would provide enhanced capability to this end — as noted in §3.1.1; however, it is not seen as plausible to fit multiple landers (plus an orbiter) within the New Frontiers cost cap. The location to place a single lander to most thoroughly address the science questions posed in §4.3.2 is an unresolved scientific matter. Placing a lander directly atop exposed polar ice (i.e., the polar caps) would provide more direct information about the rate and magnitude of ice sublimation and deposition, thus more directly addressing the question of polar sourcing of water vapor. The technical challenges associated with such a lander have been outlined in §4.1.4.

Alternatively, as proposed here, placing a lander on or near non-polar ice deposits (surface or subsurface) provides perhaps more information on the surface/atmosphere exchange, and subsurface storage (e.g., as ice or adsorbed water) that is representative of a greater fraction of the

Martian surface. It is a technically less risky endeavor to land at lower latitudes. Many of the same questions about surface/atmosphere exchange can be addressed as with a lander on polar ice deposits, but perhaps not to the same level of fidelity—such a lander would rely more heavily on the orbital component of the mission to infer details about vapor transport in the lower atmosphere. For example, by placing a lander on a non-polar ice deposit, we would lack direct information about the flux of water vapor out of the polar cap during spring and summer. However, information about column-integrated vapor abundance, as well as the vertical profile of water vapor above ~3 km from orbit, nevertheless allows one to calculate the 'missing' vapor which would necessarily be located below 3 km. A binary assessment of the depth of water vapor off the polar cap ('shallow' vs. 'deep') is still a significant finding. Combined with similar information about the structure of dust and water ice through the atmosphere, key discoveries can still be made, and several scientific challenges mitigated with a single landed platform.

Maximizing the science return from this mission concept requires integration with a robust modeling program. General circulation models (GCMs) can serve as the 'missing link' between the limited scope of orbital observation(s) and the need for global coverage. Using one lander and orbiter to profile a single column does not provide the global coverage ultimately desired; however, multiple landers placed strategically around Mars, combined with an orbiter, is out of scope for a New Frontiers-class mission. Using the retrieved data to validate GCM physics, or to identify flaws in model physics, provides a clear path forward for the modeling community. Using data assimilation techniques, atmospheric conditions at unobserved locations can be assessed. It is imperative, then, that such modeling work be incorporated as a key component of the mission science.

4.3.5. Alternative Implementations

In lieu of a single large lander targeting a single surface location, small, untargeted hard-impact landers carrying ~20 kg to the surface could provide an alternative matrix of near-surface atmospheric data (i.e., a fraction of the observations of a larger lander, but across a greater spread of the globe). Similar science questions would be addressed, but using a different approach. For example, rather than measuring the surface vapor flux at a single location, measurements of vapor abundance only, but at several locations, could be obtained. Numerical models would be relied upon to provide estimates of near-surface wind to infer surface flux, but the additional vapor data from multiple locations could provide more valuable model validation than a single, more capable lander. Such hard-impact landers, as conceived, would be equipped with solar panels for power generation. As noted in the *Supplemental Materials*, four landers were thought to fit within both launch system mass/volume and cost constraints.

As an alternative, a scaled-down version of the payload could potentially be used on even smaller landing systems which might have more restrictive volume, mass, and/or power constraints. As an example, the Mars$_{\text{DROP}}$ microprobe architecture [Williams et al., 2015] illustrates the potential science capabilities of a more restricted surface payload (§5.6). Several of the aforementioned payload components, including surface pressure, air and ground temperature, and absolute humidity instruments, could fit within the constraints of a small, targeted probe such as Mars$_{\text{DROP}}$. Lifetime of the probe would be significantly shorter (assuming such small spacecraft would rely on batteries or have limited solar charging capabilities), and so there would be reduced science return from the landed instruments. But, through careful selection of landing site and landing season, or potentially sequentially sending several landers to the same regions, a portion of the baseline science could be returned. For example, deployment of a probe in early spring near the polar cap margin could provide useful information about the rate of vapor sublimation off the retreating cap. Targeting a single region several times over multiple Mars years could provide information about the interannual variability of atmospheric conditions at that location and season. Lastly, probes deployed at disparate locations across the surface, surviving for only one or two weeks each, may nevertheless provide useful information about the boundary layer to complement orbital observations, thereby working to validate those measurements.

Table 4.3. *Science tracing to notional payload for Concept NF3: Investigation of present-day meteorology from orbit and the ground*

Science Questions	Measurement	Instrument type
How do local, regional, and global circulations control the transport of volatiles, dust, and non-condensing gases into and out of the polar regions, and how do they evolve over time? *From Priority Science Area A/§3.1:* **Q1: How does the atmosphere control the exchange of ice and dust between ice reservoirs, within global-scale horizontal and vertical transport?** Q2: How does the atmosphere control the exchange of ice and dust between ice reservoirs, within local-scale vertical transport?	A. Vertical wind profile from surface to ~80 km, acquired in such a way so as to build up a 4-D representation of global circulations B. Vertical water vapor and dust profiles from surface to ~80 km, so as to build a 4-D representation of their distribution C. Vertical temperature profiles for characterizing influence of dust and water ice clouds on global circulation D. Surface wind, vapor and dust at high frequency	(A+B) Weather camera: provide full global coverage of column-integrated dust and water ice (A+B) Orbital sub-mm sounder and LiDAR system: LiDAR may become more effective during dustier events, and regionally during periods of elevated low-level dust and ice. Retrieve water vapor profiles down to <10 km from sub-mm sounder (A) Ground-based Doppler LiDAR to retrieve wind field in the lowest ~10 km (B+C) Orbital thermal IR sounder: globally map the dust and water ice vertical profiles from the surface to upper atmosphere (D) Ground-based 3-D anemometer, absolute humidity measurement, and dust saltation/entrainment detector
What is the interannual (interdecadal?) variability of the atmospheric circulation that controls ice distribution over Mars decadal timescales? *From Priority Science Area A/§3.1:* **Q1,** Q2 Q5: What are the factors that control the current mass balance of the surface H_2O and CO_2 ices?	A. 3-D wind field over multiple Mars years B. Surface polar and non-polar ice distribution	(A) Orbital sub-mm sounder and LiDAR system: map global winds over multiple Mars years, and variability at similar locations in different years would provide a measure of interannual-variability in circulation (A) Ground-based Doppler LiDAR to retrieve wind field in the lowest ~10 km (B) Weather camera: provide global coverage of extent of surface ice
How do seasonal CO_2, H_2O, and dust cycles interact and how does this control the distribution of water ice? *From Priority Science Area A/§3.1:* Q5	A. Vertical water vapor profiles from surface to ~80 km, so as to build up a 4-D representation of their distribution B. Vertical water ice and dust profiles from surface to ~80 km, so as to	(A) Orbital sub-mm sounder to retrieve water vapor profiles down to ~10 km (A) Ground-based spectrometer capable of measuring absolute vapor abundance at the surface (B) Orbital weather camera: full global coverage of column-integrated atmospheric dust and water ice

Q4: What is the current annual net (global-scale) mass flux transport of volatiles, including H_2O and CO_2, and dust from/to polar and non-polar ice reservoirs? Q7: How is ice formed in both the atmosphere and at the surface, how are dust lifting and entrainment processes affected by in the presence of ice, and what is the radiative response to the resultant combination of ice and dust?	build up a 4-D representation of their distribution C. Vertical temperature profiles for characterizing influence of dust and water ice clouds on global circulation D. Surface pressure (for mapping the CO_2 cycle) E. Surface dust lifting and entrainment	(A+B+C) Orbital thermal IR sounder: quantify profiles of dust and water ice in the atmosphere, and measure surface temperature (C) Ground-based surface and air temperature sensors (D) Ground-based pressure sensor (E) Ground-based sand saltation detector + 3-D anemometer to determine wind thresholds for lifting
How does the seasonal polar circulation and ice deposition change in extent and magnitude during and after large global dust events (versus years without such events)? *From Priority Science Area A/§3.1:* **Q4,** Q5, Q7	A. Vertical wind profile from surface to ~80 km acquired in such a way so as to build a 4-D representation of global circulations between years with/without global dust events. B. Extent of polar caps and magnitude of atmospheric dust between years with/without global dust events.	(A) Orbital sub-mm sounder: measure polar winds over multiple years. (B) Weather camera: monitor temporal and spatial growth of large global dust events and latitudinal extent of polar caps. (B) Thermal IR sounder: measure growth and magnitude of large dust events. Identify vertical distribution of dust. (A) Surface imager to establish time-varying opacity (tau) of the global dust event.
What processes control the formation of H_2O and CO_2 clouds? How does their formation affect the vertical thermal structure (including surface temperature?) and atmospheric circulation over the poles? (Including mesospheric clouds as well as polar clouds.) *From Priority Science Area A/§3.1:* Q7	A. Temperature profiles in and around cloud formation areas, and relate cloud distribution to overlying and underlying thermal structure B. Surface temperature C. Water-ice cloud height and opacity D. Vertical wind profile from surface to ~80 km, so as to build a 4-D representation of global circulations E. Vertical water vapor profiles from surface to ~80 km, so as to build a 4-D representation of distribution	(A+B+C+D) Orbital thermal IR sounder: measure temperature profiles, water vapor and ice profiles (C) Ground-based Doppler LiDAR system: measure the cloud height for clouds lower in the atmosphere (D) Orbital sub-mm wind sounder: map the polar circulation before and after cloud formation; this is particularly useful when the polar hood clouds form and affect thermal structure (E) Orbital sub-mm wind sounder to retrieve water vapor profiles down to ~10 km (E) Ground-based spectrometer capable of measuring absolute vapor abundance at the surface

Are the non-polar ice deposits contributing to the current day water cycle and polar processes? *From Priority Science Area A/§3.1:* Q5, Q7	A. Near-surface vapor distribution B. Near-surface winds	(A+B) Ground-based spectrometer capable of measuring absolute vapor abundance at the surface, plus a high-frequency anemometer to determine surface vapor flux
What atmospheric processes (mechanisms) control the deposition and removal of water ice on the polar layered deposits (PLD)? *From Priority Science Area A/§3.1:* **Q1,** Q2, Q5, Q7 **Q6: What are rates of deposition and removal of ice and dust on the residual caps in the current climate?**	A. Near-surface temperature profiles B. Near-surface water vapor distribution C. Near-surface winds	(A) Ground-based surface and air temperature sensors (B) Ground-based spectrometer capable of measuring absolute vapor abundance at the surface (C) Ground-based high-frequency anemometer. Together, B+C would yield surface vapor flux
To what extent are dust storms controlling the deposition/sublimation of ices in non-polar regions? *From Priority Science Area A/§3.1:* **Q1,** Q2, Q5, **Q6,** Q7	A. Ice extent in non-polar regions B. Temporal growth/ extent of dust storms C. Temperature profiles over ice deposits in non-polar regions and within dust events. D. 3-D dust and water vapor distribution over non-polar ice	(A+C+D) Thermal IR sounder: map surface temperature and atmospheric dust (A+B) Weather camera: observe the ice extent in non-polar regions, and the extent of dust storm activity coincident with ice behavior (D) Orbital sub-mm sounder for obtaining water vapor profiles above ~10 km
How do seasonal CO_2, H_2O, and dust cycles control the vertically and horizontally distributed radiative heating in the atmosphere? *From Priority Science Area A/§3.1:* Q5, Q7	A. Dust and water ice vertical profiles B. Temperature profiles C. Global monitoring of dust and ice clouds D. Net surface energy balance	(A+B) Thermal IR sounder: profile dust and water ice aerosols, and measure vertical temperature profiles (C) Ground-based Doppler LiDAR: obtain cloud and/or dust height in the boundary layer (C) Weather camera: context of water ice and dust location and extent (D) Surface bolometer or radiometer to measure downward and upward energy fluxes

4.4 Concept NF4: Investigate vertical structure of mid-latitude ice

4.4.1. Concept Overview

The evolution of Mars' ice and climate is recorded in a number of locations, including the mid-latitude regions of Mars. Therefore, exploration of the surface of Mars at the mid-latitudes is a powerful way to expand our understanding of Martian ice and climate evolution. Using the current state of knowledge of the boundary layer meteorology and climatology and the distribution and composition of volatile reservoirs in the shallow subsurface, we considered a stationary landed mission capable of drilling and borehole measurements and including meteorology instrumentation. The most useful landing location would be the southernmost latitude within the northern plains where subsurface ice has already been detected within 50 cm of the surface. Below we focus in detail on this mission concept's architecture, followed by a brief description of alternative implementations and an alternative mission architecture.

Table 4.4 details a notional lander payload that could address a number of science questions in all five ICE-SAG Priority Science Areas, and is focused on understanding boundary layer meteorology, subsurface ice reservoirs, and volatile exchange between subsurface ice, regolith, and atmosphere. The lander would perform several key measurements, some of which require daily observations for at least one Mars year and hourly observations over some sols.

Note that JPL's Team X provided a cost model of a similar implementation to this lander, which included a drill, TEM loop, and additional 22 kg of unspecified payload mass. Individual instruments within the payload were not assessed, and borehole measurements were not included. The lander was assumed to be located at a site near ~60°N (further north than necessary to access shallow ice, and so a conservative choice for assessing power needs) and operating on solar power for one year. Under these constraints, the cost was estimated to be just under the New Frontiers cap (Supplementary Materials).

4.4.2. Science Questions Addressed

The notional lander would address questions related to volatile transport, subsurface ice concentration and vertical structure, mechanisms of volatile exchange, and the abundances and conditions of formation of liquid water, if any. Top level questions (organized by Priority Science Area), include:

- *What controls the vertical movement of volatiles and dust from the boundary layer to the top of the atmosphere in non-polar ice regions?* (**Priority Science Area A, §3.1**) A stationary lander would capture the boundary layer and lower atmospheric state at multiple timescales, including the distribution and transport of H_2O and CO_2 in the lower atmosphere. Repeated imaging would allow for tracking of frost formation in an non-polar region. Concurrent use of a meteorological station and vertical LiDAR would allow for understanding the atmospheric conditions and role of dust storms, cloud formation, etc. in affecting frost formation. This payload would also provide information into how frequently changing, small scale atmospheric features (e.g., water ice clouds, CO_2 clouds, dust distribution) affect atmospheric radiative balance, surface temperature and vertical thermal structure in the atmosphere.
- *How much interaction does mid-latitude ice have with the atmosphere? And by what mechanisms?* (**Priority Science Area A, §3.1**) The lander payload would provide detailed characterization of the ice distribution and isotopic compositions, as well as the physical and mineralogical characteristics of the non-ice overburden, which are necessary to

investigate how near-surface mid-latitude buried ice was formed, and how it is preserved in today's climate. Water vapor density and mixing ratio measurements in the subsurface, surface and boundary layer, over multiple time scales, as well as monitoring of subsurface adsorption and hydration, would contribute to our understanding of ice-atmosphere exchange mechanisms. This would help elucidate how and if non-polar subsurface ice deposits contribute to the current day water cycle.

- *What is the concentration and vertical structure of ice in mid-latitude subsurface deposits?* (**Priority Science Areas B/C, §3.2 and §3.3**) The notional lander would measure the porosity, ice concentration, grain size, and mineralogy of the upper ~1 meter of the surface and provide additional information on ice structure and concentration down to at least 20 m depth. Repeated imaging would allow for the tracking of potential small-scale movements related to frosts, subsurface ice and volatile exchange (e.g., soil movement at polygon troughs). Tracking of small-scale processes over the long term could provide insights into how subsurface ice affects landform development at a larger scale.
- *Are liquid H_2O-bearing phases occurring at or near the surface? When, where, how, and how much?* (**Priority Science Area E, §3.5**) Thermal conductivity and electrical resistivity measurements would permit monitoring of the formation of liquid phases and, combined with subsurface and surface RH and temperature measurements, allow linkage with atmospheric conditions. Monitoring of changes in adsorption, mineral hydration, and deliquescence, with depth, would help to quantify the magnitude, timescales and environmental conditions associated with those changes. Vertically resolved measurements of mineralogy and amorphous species identification would provide critical inputs into laboratory studies designed to understand the long-term effects of thin films and deliquescence on soil chemistry and physical properties and on the landscape (§6.2).

4.4.3. Measurements and Conceptual Instrument Suite

- ***X-Ray Micro-Computed Tomography (MicroXCT)*** (§3.3.1): XCT has also been used with some success to map the cryostratigraphy and ice content of terrestrial permafrost ice cores, with some limitations related to the voxel resolution [e.g., Lapalme et al., 2017]. However, *Micro*-XCT can achieve voxel sizes on the order of microns [Obbard et al, 2009] and could potentially be utilized in conjunction with a coring drill to scan cored material as the drill is removed from the subsurface.
- ***Transient Electro-Magnetic survey (TEM) or other geophysical methods*** to interrogate the subsurface structure (§3.3.1).
- ***Tunable laser spectrometry (T-LS)*** to measure isotopic and chemical compositions of samples (§3.3.1).
- There are multiple spectral techniques for measuring mineralogy, however, ***Raman or thermal infrared spectroscopy*** are most capable of distinguishing between X-ray amorphous phases [e.g., Minitti et al., 2010; Rampe et al., 2012; Fu et al., 2017; Sklute et al., 2018]. This is important because MSL has shown the amorphous fraction of the regolith at Gale crater comprises up to ~45% of the bulk soil, and also, hosts most of the hydrated phases in the soil [e.g., Bish et al., 2013; Leshin et al., 2013]. Because mineral hydration/dehydration is sensitive to RH [e.g., Vaniman et al., 2004], this process is one potential mechanism for surface-atmosphere H_2O exchange. Thus, to fully characterize the mechanisms and kinetics of surface-atmosphere exchange, it is important to identify the

phases that host molecular H_2O, including the amorphous phases, and to measure changes in hydration state.

- H_2O adsorption is also a likely mechanism of surface-atmosphere exchange, and thus also should be measured. ***Short-wave IR spectroscopy*** is particularly sensitive to adsorbed water, near ~3µm, ~1.4 µm, and ~1.9 µm [e.g., Bishop et al., 1994; Yen et al., 1998], as well as bound/molecular water. Ideally, spectral measurements could be taken inside the borehole, over a period of 1 Mars year. Concepts for fiber optic-based spectrometers have been put forward, [e.g., Pilgrim et al., 2009], where the light source and measured energy are transmitted through fiber bundles encased in IR transparent probe shafts. This configuration could potentially allow for high vertical resolution measurements of mineralogy as the probe is deployed downward, and then lower vertical resolution, but long-baseline temporal measurements of changes in adsorption, hydration state or phase change once the probe is in place.
- ***A comprehensive meteorology station*** (§3.3.1) would provide the measurements required to investigate the conditions that control aeolian and atmospheric processes at Mars' surface and in Mars' near-surface atmosphere.
- **An *upward-looking LiDAR instrument*** would allow the mission to measure the vertical profile of water vapor and dust (§3.3.1).
- ***Visible and thermal cameras*** would allow tracking of surface changes, including minor freeze-thaw processes and frost species, and would permit derivation of thermal inertia of the upper surface layer within the landing site region.
- **Temperature-RH and electrical resistivity probes** in the shallow subsurface would be used to link subsurface and near-surface water vapor changes and to track changes in H_2O state.

The notional lander would deploy the TEM loop, MET station instrumentation, and subsurface temperature-RH probe to begin hourly monitoring. It would then drill through the icy regolith to a depth of at least 1 meter. Micro-computed x-ray tomography would be used to measure the 3-dimensional structure (grain size, porosity) and composition of the cored material as the drill is removed from the subsurface. In addition, the borehole material would be discharged into sequential sample cups and delivered into the lander for T-LS analysis. A probe with IR-transparent casing or windows, containing fiber optic bundles conducted to Raman and SWIR IR spectrometers would be slowly deployed downward into the borehole. Ideally, fiber optics would be pointed at different directions around the circumference of the probe, and spaced out along the shaft in ~5-10 cm increments. During deployment, mineralogy would be measured in multiple directions and with high vertical resolution. Once fully deployed, the spectrometers would then be used to monitor changes in adsorption and hydration state over the course of the mission. A visible camera system would be used to detect surface changes over the course of the year and to place the setting of the ice core in geomorphic context, helping to bridge the gap between orbital and surface observations. The camera would also be able to track the occurrence of surface frost.

4.4.4. Key Technical or Science Challenges

- A key science challenge is to determine the degree to which the lander and borehole would affect the natural environmental parameters that the mission is designed to measure. For example, how does the lander affect the boundary layer conditions? (§5.3) At what distance from the lander is that effect negligible? How would the borehole affect the efficiency of volatile exchange between the surface and subsurface? (§5.5)

- Technical challenges include investigating the feasibility of T-LS and/or IR measurements inside the borehole, and the constraints on those measurements. (§5.5**)**

4.4.5. Alternative Implementations

There are a number of descope options or alternative implementations for this mission concept that would lower costs and complexity while still resulting in a scientifically exciting mission. These include:

1. *Descope*: TEM/geophysical survey – no structural information below 1 m depth – moderate impact to Question 5 (Table 4.4).
2. *Descope*: Only one spectrometer (likely SWIR) – get adsorption and hydration state information, but not detailed amorphous mineralogy – moderate impact to Questions 8-10 (Table 4.4).
3. *Descope*: LiDAR – Severe impact to Questions 2 and 7 (Table 4.4), no aerosol / cloud formation information.
4. *Alternative implementation*: No borehole science. Severe impact to Questions 4, 5 and 6 (Table 4.4). Possibly augment T-LS with GCMS and micro-Raman inside the lander to reduce impact to investigation 4.
5. *Alternative implementation*: T-LS inside the borehole and no science instruments inside the lander.

An alternative mission architecture would use multiple stationary landers distributed across a range of northern latitudes, to measure shallow ground ice and ice-free surfaces in the northern plains. A notional payload for each lander would include *(a)* a TEM survey plus dielectric spectroscopy to assess subsurface structure and H_2O state, *(b)* a subsurface RH probe, *(c)* a visible camera system and *(d)* a capable meteorology station. This mission concept trades vertically resolved regolith porosity and ice concentration measurements and understanding mechanisms of surface-atmosphere exchange for detailed characterization of ice distribution, surface-atmosphere interactions, and boundary layer processes as a function of latitude, thereby providing an important spatial component to understanding these processes. Although the instrumentation would be more limited, this spatial distribution would be independently valuable because of the diversity of settings of mid-latitude ice.

Table 4.4. *Science tracing to notional payload for Concept NF4: Investigate vertical structure of mid-latitude ice*

Science Questions	**Measurement**	**Instrument type**
1. What controls the vertical movement (i.e., surface/atmosphere exchange, deposition, abrasion, sublimation, and mixing) of volatiles and dust from the boundary layer to the top of the atmosphere in both polar and non-polar regions with ice deposits? *From Priority Science Area A/§3.1:* **Q1: How does the atmosphere control the exchange of ice and dust between ice reservoirs, within global-scale horizontal and vertical transport?** Q2: How does the atmosphere control the exchange of ice and dust between ice reservoirs, within local-scale vertical transport?	Integrated: A. atmospheric temperature, volatile content, an wind speed in a manner by which the eddy fluxes can be derived (or directly measured) B. pressure measurements C. ground temperature measurements	(A+B+C) Comprehensive Meteorology Station
2. What is the distribution and transport of H_2O and CO_2 in the lower atmosphere and how does it vary at daily, seasonal and multi-annual timescales? *From Priority Science Area A/§3.1:* Q2 **Q4: What is the current annual net (global-scale) mass flux transport of volatiles, including H_2O and CO_2, and dust from/to polar and non-polar ice reservoirs?**	A. vertically-resolved gaseous H_2O and CO_2 concentrations from surface to above the boundary layer	(A) Vertical observing LiDAR
3. How much interaction does mid-latitude ice have with the atmosphere? And by what mechanisms? 6. How do diurnal, seasonal, and multi-annual atmospheric cycles affect and/or control the distribution of ice in the atmosphere and on the surface? *From Priority Science Area A/§3.1:* **Q1,** Q2 Q5: What are the factors that control the current mass balance of the surface H_2O and CO_2 ices?	A. shallow subsurface regolith relative humidity and near-surface atmospheric humidity, monitored for at least 1 MY B. subsurface ice concentration as a function of depth C. isotopic compositions of subsurface ice and the atmosphere	(A+C) Comprehensive Meteorology Station (A) Subsurface RH-T probes (B) TEM/geophysical survey (B) Micro-XCT (C) T-LS

4. Are ice-related surface features evolving today? *From Priority Science Area B/§3.2:* Q10: Which parts of the Martian surface have been or are currently formed or modified due to ice-driven processes?	A. observations of surface changes, including frost formation and freeze/thaw processes	(A) Visible and Thermal Imaging
5. What is the concentration of ice in mid-latitude subsurface deposits and how does it vary, both laterally and vertically? *From Priority Science Area B/§3.2:* **Q8: Where does subsurface water ice presently exist, and at what depth?** **Q9: What is the volume and purity of water ice present in the non-polar ice reservoirs?** *From Priority Science Area C/§3.3:* Q13: What composes and defines a layer, in the mid-latitudes?	A. regolith porosity and grain size with depth, to at least 1 meter B. ice concentration with depth to at least 20 m	(A) Micro-XCT (B) TEM/geophysical survey
7. To what extent do frequently changing, small scale features (e.g., water ice clouds, CO_2 clouds, dust distribution) affect the atmospheric radiative balance? *From Priority Science Area A/§3.1:* Q7: How is ice formed in both the atmosphere and at the surface, how are dust lifting and entrainment processes affected by in the presence of ice, and what is the radiative response to the resultant combination of ice and dust?	A. opacity of water ice clouds, CO_2 clouds and dust distribution B. corresponding radiation flux at the surface and top of the atmosphere	(A) Vertical observing LiDAR (B) net radiation sensors

8. Are liquid H_2O-bearing phases occurring at or near the surface? When, where, and how much? Does change occur slowly through microvolumes, or in a more punctuated manner involving macrovolumes (e.g., flowing) of liquid? How abundant/common are thin films today? In permafrost (i.e., premelting)? At/near surface (deliquescence)? 9. What is the present-day stability state of subsurface ice, and where is it being deposited or removed? How effectively is it preserved during periods of instability? 10. What is the effect of liquid phases on soil chemistry and physical properties? What are the long-term, macroscale effects of liquid phases on the landscape (e.g., duricrust, solifluction, frost heave, flow)? *From Priority Science Area E/§3.5:* Q20: Which surface features may be formed or modified by the flow of relatively large amounts of liquid water? Q21: How do volatiles and volatile-driven processes cause Martian surface activity?	A. changes in H_2O adsorption, as a function of depth, to at least 1 meter, for at least 1 MY B. changes in mineral hydration state or phase, as a function of depth, for at least 1 MY C. regolith mineralogy (including amorphous phases) as a function of depth, to at least 1 meter	(A) electrical resistivity probe (B+C) Short-wave IR spectrometer; Raman or TIR reflectance spectrometer

4.5 Concept NF5: Map the distribution, structure, and activity of near-surface ice

4.5.1. Concept Overview

To understand global climate and link current surface–atmosphere interactions to a record of recent paleoclimate, a global inventory of surface and near-surface ice is needed, along with quantification of change. This mission concept is for an orbiter designed to detect and characterize ice in the near subsurface (0–100 m), map stratigraphy at higher resolution than previous radar sounders, map topography at high resolution, detect and quantify surface change, and map surface composition. This concept builds upon and expands on portions of the 2015 concept presented in the MEPAG-commissioned study for the Next Mars Orbiter – NEX-SAG. Emerging from the NEX-SAG report were five areas of new compelling science. One primary area of new science was to map and quantify deposits of shallow ground ice across Mars along with shallow layering of volatile ices at the poles to better understand the global volatile inventory. The mission concept presented here also includes quantifying current-day surface change as well as high-resolution stratigraphy and composition that are linked to the NEX-SAG [2015] compelling science objective D: to characterize the occurrence and timing of major environmental transitions.

4.5.2. Science Questions Addressed

This mission concept aims to push beyond the current state of knowledge to provide an enhanced and comprehensive characterization of Martian ice reservoirs. Using an orbital platform would provide a global perspective of the diverse Martian ice deposits, and the chosen suite of instrumentation would examine their nature to a depth of 100 m, satisfying **Priority Science Areas B and C**. It would also help to address Questions within Priority Science Area A (§3.1) and Priority Science Area E (§3.5). Furthermore, delivering instruments that are complementary to those of MRO and other missions to Martian orbit would enable continued or even simultaneous surface-change monitoring. Seasonal changes associated with volatiles, including the advance and retreat of frosts (CO_2 and H_2O) and erosional activity within the PLDs such as avalanches and CO_2 pit growth, inform understanding of volatile transport processes.

The specific questions addressed by this mission concept are:

- *What is the current annual net (global-scale) mass flux transport of volatiles, including H_2O and CO_2, and dust from/to polar and non-polar ice reservoirs?* (**A, Q4, §3.1**). A critical part of addressing this question is mapping the thickness of seasonal deposits at the poles from orbit.
- *Where does subsurface water ice presently exist, and at what depth?* (**B, Q8, §3.2**).
- *What is the volume and purity of water ice present in the non-polar ice reservoirs?* (**B, Q9, §3.2**).
- *Which parts of the Martian surface have been or are currently formed or modified due to ice-driven processes?* (**B, Q10, §3.2**).
- *Where is CO_2 ice present in the subsurface?* (**B, Q11, §3.2**).
- *What composes and defines a layer in the PLDs?* (**C, Q12, §3.2**).
- *What composes and defines a layer in the mid-latitudes?* (**C, Q13, §3.2**).
- *Which surface features may be formed or modified by the flow of relatively large amounts of liquid water?* (**E, Q21, §3.5**).

4.5.3. Measurements and Conceptual Instrument Suite

- ***Interferometric, polarimetric SAR (InSAR)***– This is an L-band (1 GHz) synthetic aperture radar that uses dual antennas to map high-resolution topography (cm accuracy) in a single pass and detect surface change with multiple passes. It can detect a polarimetric signature of ice in the shallow subsurface, with meters of penetration through the regolith. Horizontal resolution is ~20 m, with ~5 m possible using a spotlight mode in select areas.
- ***Dual-band radar sounder*** **–** This radar sounder would operate at two center frequencies such as 250 MHz and 500 MHz, with 50% bandwidth, to probe the subsurface at much higher resolution than MARSIS and SHARAD. It would produce maps of shallow structure including the vertical distribution of ice whose presence is detected by InSAR, at 0.5 – 1 m vertical resolution. It would map the thickness of debris/regolith cover for mid-latitude buried ice, and would produce high-resolution (~1-m scale) stratigraphy in the PLD to depths of 100–1000 m, with footprints of < 1 km.
- ***Imaging Spectrometer*** **–** Similar to CRISM, covering portions of the visible and short infrared spectrum, but with higher spatial resolution (10 m) needed to confirm detections of surface ice, discriminate between H_2O and CO_2 ice, and to produce compositional maps at scales similar to the InSAR in spotlight mode.
- ***Thermal Imager*** **–** Spanning portions of the visible and thermal infrared spectrum, this instrument would characterize physical properties of the regolith over features indicative of ice, and where ice is detected in the shallow subsurface with radar. It would have resolution cells larger than the InSAR and imaging spectrometer, but would provide critical context and physical properties otherwise unattainable.
- **High-resolution visible camera –** A visible camera with color capability, high signal-to-noise ratio, and resolution at minimum superior to CTX (6 m/pix), with finer pixel scales up to that of HiRISE (30 cm/pix) providing progressive increases in science benefit, cost, and mass. This camera would provide geologic and geomorphic context for the other instruments, detect new ice-exposing impacts, and provide surface imagery simultaneously with other data sets, which has proven to be of high value in all studies of surface changes, and thus provides a benefit unobtainable from use of CTX or CaSSIS data.

4.5.4. Key Technical or Science Challenges

- **Clutter for the radar sounder.** For sounding radars, a means to mitigate or account for undesired off-nadir returns (clutter) that interfere with or can be mistaken for nadir subsurface returns is critical, and can often be challenging. The DTM provided by simultaneous InSAR imaging would allow for the production of clutter simulations at an appropriate scale for discriminating clutter from subsurface returns.
- **Accommodation of two radar systems on the spacecraft.** NEX-SAG [2015] developed a similar mission concept, and this involved much discussion about how to accommodate one spacecraft on the orbiter. In this concept, other large systems, such as the sample cache-catching system, are not included. However, a study of accommodation and resource-needs for the concept described here was not completed within this SAG.

4.5.5. Alternative Implementations

Descope Options

1. Remove Thermal Imager: This descope reduces cost, mass, and complexity with the least impact on the overall objectives. Characterization of regolith covering ice in the mid-latitudes would be more difficult.
2. Remove high-resolution visible camera: This descope reduces cost, mass, and complexity, with the primary impacts being the loss of change detection at visible wavelengths and the loss of simultaneous imaging that supports other instruments. Visible data from other missions (CTX, CaSSIS) could substitute for morphological context.
3. Remove Imaging Spectrometer: This descope reduces cost, mass, and complexity, and primarily impacts the ability to confirm the presence of ice at the surface in exposures such as recent impact craters, sublimating scarps, and other short-lived phenomena.
4. Reduce from dual- to single-antenna SAR, with repeat-pass interferometry instead of single-pass: This descope reduces complexity of the InSAR deployable antenna system, and mass. This would require multiple passes to generate topography, and then two additional repeats to detect change. Coverage of both topographic mapping and change detection would be greatly reduced compared to dual-antenna, single-pass InSAR.
5. Reduce from dual- to single-band sounder: This descope would reduce cost, mass (marginally, given shared hardware), data volume and complexity. Characterization of the shallow subsurface structure and composition would suffer. A trade would have to be made in order to prioritize either penetration or resolution.

Table 4.5. *Science tracing to notional payload for Concept NF5: Orbiter to map and characterize ices*

Science Questions	**Measurement**	**Instrument type**
From Priority Science Area A/§3.1: **Q4: What is the current annual net (global-scale) mass flux transport of volatiles, including H_2O and CO_2, and dust from/to polar and non-polar ice reservoirs?**	A. Thickness and distribution of seasonal CO2 deposits at poles to 0.25 m vertical and 20 m horizontal accuracy. B. CO_2 vs H_20 ice discrimination	(A) InSAR (B) Imaging Spectrometer
From Priority Science Area B/§3.2: **Q8: Where does subsurface water ice presently exist, and at what depth?**	A. Circle Polarization Ratio measurements of shallow subsurface B. Subsurface reflectors C. Dual-frequency permittivity/loss tangent estimates	(A) SAR (B) Radar sounder (C) Radar sounder
From Priority Science Area B/§3.2: **Q9: What is the volume and purity of water ice present in the non-polar ice reservoirs?**	A. Subsurface reflectors B. Dual-frequency permittivity/loss tangent estimates	(A) Radar sounder (B) Radar sounder
From Priority Science Area B/§3.2: Q10: Which parts of the Martian surface have been or are currently formed or modified due to ice-driven processes?	A. Geomorphological characterization of potential ice-related landforms B. Compositional characterization of potential ice-related landforms	(A) Camera, InSAR (B) Imaging Spectrometer, Thermal Imager, Radar sounder
From Priority Science Area B/§3.2: Q11: Where is CO_2 ice present in the subsurface?	A. Circle Polarization Ratio measurements of shallow subsurface B. Subsurface reflectors C. Dual-frequency permittivity/loss tangent estimates	(A) SAR (B) Radar sounder (C) Radar sounder
From Priority Science Area C/§3.3: Q12: What composes and defines a layer, in the PLDs?	A. High-resolution stratigraphy in upper PLD B. High-resolution surface topography	(A) Radar sounder (B) InSAR, Camera
From Priority Science Area C/§3.3: Q13: What composes and defines a layer, in the mid-latitudes?	A. Shallow ice distribution and vertical structure in mid latitudes B. High-resolution surface topography	(A) Radar sounder (B) InSAR, Camera (stereo)
From Priority Science Area E/§3.5: Q21: Which surface features may be formed or modified by the flow of relatively large amounts of liquid water?	A. High resolution surface topography B. Imagery	(A) InSAR, Camera (stereo) (B) Camera

4.6 Concept SS1: Small Landers for Gully and RSL Locations

Due to ongoing debates about their specific formation mechanisms and drivers (described in §2.4.3), large-scale investigations of RSL and gullies were not considered the top priority for advancing understanding of Martian climate history by ICE-SAG. However, determining their formation mechanisms and drivers are of considerable interest as that would connect observable landforms and activity to present-day environmental conditions and processes – feeding into Priority Science Area E (§3.5). Towards that aim some valuable in situ exploration could be conducted by small spacecraft or Discovery-class missions. While larger missions could potentially conduct more comprehensive investigations, they are not discussed here.

Several relatively simple observations could make valuable contributions from nearby an active gully or RSL location (but not directly on such features, so as to avoid Planetary Protection concerns). Most obviously, observing either type of flow in action would provide essential insights. For RSL, it would be possible to test whether the advance is via a series of grainflows following the same track, or gradually seeping liquid. At gully locations, no CO_2-charged flow has ever been observed in nature, and imaging or video would provide important information about the flow dynamics. Given sufficient storage, a lander could collect imaging data frequently and only return the full set for intervals of interest. A landed mission would be able to pin down the speed and timing of flows with much greater precision than possible from orbit. Additionally, landed imaging would provide information about the settings, such as a higher-resolution view of the material properties. Observations made on a gully fan could reveal the grain sizes transported by recent flows or show structures formed by loss of CO_2 ice.

Additional data about environmental conditions would greatly supplement this basic investigation. For gullies, the most important information is the presence, amount, and composition of seasonal frost. A thermal or near-infrared spectrometer could provide these data. For RSL, the highest priority is basic meteorological information such as pressure, temperature, relative humidity, and wind speed and direction; the latter is of significant importance for understanding the behavior of grainflows, and the former three are important to understanding the possibility of liquid. If landed on an RSL fan, the most valuable measurements would be the electrical conductivity and relative humidity of the shallow subsurface, which could directly test for the presence of liquid.

Some RSL locations are highly active every year [e.g., Stillman et al., 2017] and could be targeted with a high degree of confidence. Activity in individual gullies is more stochastic but some locations have been active repeatedly in the last decade [Dundas et al., 2017a], and observations of the setting would be of value even if a flow were not observed in action. We also note that some locations have shown both RSL and flows within gullies within close proximity.

Missions to RSL or gully locations do face significant challenges. Since both are sub-km-scale features, a high degree of landing accuracy (or multiple less-accurate landers, e.g., Grimm et al. [2018]) would be required to ensure that the slope feature is in view of the instrumentation; this problem is exacerbated for any measurements that must be made on the feature. Second, both RSL and gullies are considered possible Special Regions [Rummel et al., 2014] and many occur at locations where ground ice may also be present, which requires a high level of spacecraft cleanliness for Planetary Protection (although this potentially enhances relevance to astrobiology investigations, §3.6). Lastly, as gullies are active in the winter, a mission targeting them must be capable of not only surviving but also gathering data in winter in the mid-latitudes (§5.2). SmallSat missions in particular may face limiting constraints on power and on the volume of data collected and returned. Further study would be required to establish the practicality of conducting such missions.

4.7 Concept SS2: Small Spacecraft for In Situ Investigation of the NPRC and Atmosphere

Key measurements for understanding the present-day climate and layer formation in the PLD can be achieved by small landers on the surface of the north polar residual cap (NPRC). In this concept, a set of distributed "micro-landers" (~1 kg payload) would perform meteorological measurements and sample the ice to constrain the near-surface winds, humidity, temperature, and ice composition [Hayne et al., 2018]. With a simple, lightweight payload, this mission concept would provide pioneering measurements necessary to link the present-day Martian atmosphere to layer formation and the climate variations recorded in the PLD [Smith, I.B., et al., 2018b].

Due to its relatively uniform surface and low elevation (-2 km from the areoid), the NPRC is an ideal target for micro-landers with relatively large landing ellipses (up to ~100 km). Once on the surface, these probes would deploy a compact, yet capable suite of meteorological instruments, including sensors for temperature, pressure, humidity, as well as an anemometer for measuring the vector wind field. With sufficient payload accommodation, the micro-landers could also carry a sampling unit consisting of a heat probe with sample inlet, coupled to a gas analytical instrument, such as a tunable laser spectrometer or mass spectrometer. With this sampling capability, it would be possible to determine the volatile composition of the uppermost ice layer(s), including isotope ratios of key species, such as D/H [Webster et al., 2013; Villanueva et al., 2015].

With the above payload, the micro-lander mission concept would address the following science objectives: *1)* constrain and validate mesoscale models of polar atmospheric circulation, boundary layer turbulence, and volatile exchange; *2)* resolve the thinnest layers in the PLD to constrain rates of accumulation/ablation and link to orbital observations; 3) Determine isotopic fractionation recording volatile exchange in the PLD. These science objectives trace directly to several of the science questions in Priority Science Areas A (§3.1) and D (§3.4)**.**

4.8 Concept SS3: Small Spacecraft for Atmospheric Characterization

Radio occultation observations provide accurate atmospheric profiles of temperature, pressure, and number density in the neutral atmosphere at high vertical resolution (<1 km), with depth of atmospheric penetration potentially primarily limited by topography – thus feeding into questions within Priority Science Area A (§3.1). The retrieved geopotential height information, together with temperature, provides critical insight into global circulations and structure [Paetzold et al., 2016; Tellmann et al., 2013]. In the polar region, radio occultation measurements can be used to constrain the energy balance and the composition of the atmosphere in the presence of CO_2 condensation and sublimation [Colaprete et al., 2008; Noguchi et al., 2014].

While past and ongoing radio occultation investigations have occurred between a Mars orbiter and the Earth (as discussed in §3.1.1), having occultation observations occur between two Mars orbiters can allow for higher-resolution profile information to be gathered, over much more of the Martian surface. Here we consider a mission concept that would employ a constellation of small satellites around Mars equipped to generate global occultation measurements. A constellation of small satellites making radio occultation measurements could address the following science objectives: *1)* Globally map the temperature and pressure structure of the atmosphere at high vertical resolution over diurnal and seasonal timescales, including within the boundary layer and even in the presence of aerosol loading; and *2)* Constrain the energy balance and atmospheric composition in the polar regions over seasonal timescales. The number and coverage (spatial and temporal) of radio occultation profiles depends on the number and locations of satellites. Previous studies have focused on the coverage that could be obtained with as few as four small satellites [e.g., Williamson et al., 2017; Schulter et al., 2017], but more work would be needed to determine the number of satellites required to fully address specific objectives.

Small-satellites are well suited to conduct radio occultation measurements as the mass and power requirements for the heritage equipment needed (radio, antennae, electronics) can fit within typical ~6-U cubesat designs [e.g., Schulter et al., 2017; Williamson et al., 2017]. Further, the recent success of the MarCO satellites [Klesh and Krajewski, 2015] demonstrate the cubesat technology ability to operate at interplanetary distances. Work is ongoing for further technology development and demonstration to show that small satellites can orbit Mars and achieve the necessary pointing accuracy for occultation observations. Additionally, it would be important to establish the minimum atmospheric altitude that could be observed. At this time, multiple groups appear to be considering this type of mission concept, and given the rate of advancement in this area, it seems reasonable to assume that such a mission concept could be feasible in the next decade.

5 Key technological challenges and constraints on Ice and Climate focused Mars missions

In this Section, we outline technological challenges that came up in ICE-SAG discussions of needed measurements (§3) and mission concept development (§4). Investments in technology development that would address these technological challenges would enable or greatly enhance the ability to achieve the measurements needed to answer high-priority Mars ice and climate questions (§3). As will be discussed this in this section, ICE-SAG finds the following:

> **ICE-SAG FINDING 15.** Key areas of technology development would enhance or enable acquisition of needed measurements. These include technologies to address surviving the polar night, avoidance of surface contamination as well as subsurface contamination while acquiring samples, landing in the poles at a specific time of year, and reduction in the cost of delivering payloads to the martian surface.

5.1 Surviving and observing through the polar night

Survival throughout polar night is a significant technical challenge with no tested solutions to-date. During the polar night, the annual low temperature of ~150 K persists -- at high-latitudes, these conditions persist for over half of the Mars year. Survival of the spacecraft through this period requires heating to keep electronics within acceptable temperature ranges; even in a hibernation state, significant heating may be needed. Operation of instruments may require yet more heating for electronics, lubricants, etc. to behave as expected, as well as power for operations — although we note that based on the Team X study of a polar lander that would collect environmental observations through the polar night, the heating needs significantly dominated operational needs (see *Supplemental Materials*); thus turning off all instruments partway into the polar night was not sufficient for spacecraft survival.

Operating actuators and wheels in such cold temperatures would require technological advances in lubricants and materials; however, for most mission concepts, the mobility requirements and most of the operations would occur when the sun is up, and the atmosphere is warmer. (One benefit of the consistent low temperatures is that there would be far fewer thermal cycles, so stresses on soldering joints and electronics may be reduced compared to lower latitude conditions.)

Additional concerns include keeping specific surfaces frost-free, for either operations/observation concerns or spacecraft safety. As shown by Phoenix, CO_2 build-up can pose a serious mechanical threat — the spacecraft's flat solar panels were broken by seasonal frost deposition (Fig. 5.1).

Currently, the only proven power and heating sources for Mars surface missions are nuclear (i.e., an RTG for heating and power, or RHU(s) for heating) or solar. Solar power obviously cannot generate power during polar night, and current battery technologies cannot store sufficient amounts of energy to last this time (based on the Team X study, at 82°N batteries would provide sufficient power for survival over ~8 sols). RTGs are a possibility, and do not yield planetary protection concerns regarding induced Special Regions at high latitudes, as the polar environment is considered too cold to be hospitable, even if a temporary Special Region was created due to, e.g., the RTG crashing into the surface [Rummel et al., 2014]. The Team X study showed that an MMRTG provides more than sufficient power and heat for a lander at 82°N but also would create an abundance of thermal waste that could risk perturbing the frosted environment being studied

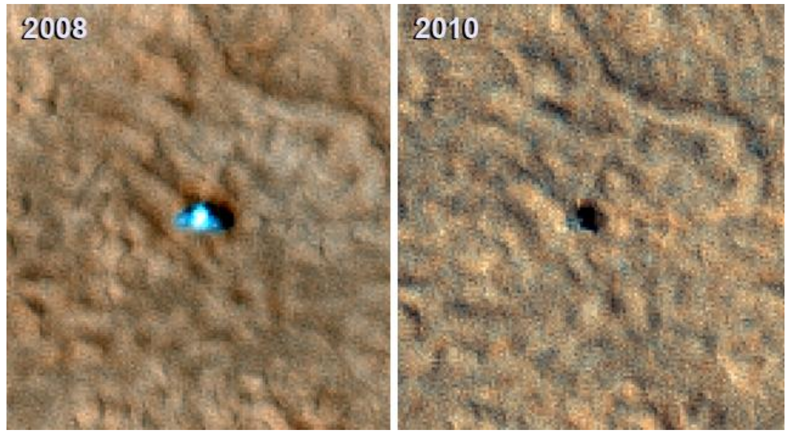


Figure 5.1. *Two images of the Phoenix Mars lander taken from Martian orbit in 2008 and 2010. The 2008 lander image shows two relatively blue spots on either side corresponding to the spacecraft's clean circular solar panels. In the 2010 image scientists see a dark shadow that could be the lander body and eastern solar panel, but no shadow from the western solar panel. It is thought that the panels were broken under the weight of seasonal frost. Image credit: NASA/JPL-Caltech/University of Arizona* https://www.nasa.gov/mission_pages/phoenix/news/phx20100524.html

and/or destabilizing the icy surface beneath the lander. A theoretical smaller RTG was considered in the Team X study that would generate ~½ the power of an MMRTG (see "Next-Gen RTG" discussion in *Supplemental Materials*). A smaller RTG was found to provide sufficient power with far less waste heat, which yielded lower cost estimates related to mass and accommodation (including shielding).

Alternatively, one could consider RHUs for heating, and power from notional alternative source such as powersticks [Pustovalov et al., 1999] or wind-driven turbines [e.g., Holstein-Rathlou, et al., 2018; *personal communication from Don Banfield*]; or both power and heating from an alternative source. Technical development is required to advance such concepts, and could be especially important given the avoidance of waste heat and any planetary protection concerns about naturally occurring Special Regions.

Some additional directions to consider are (1) having the spacecraft survive as long as possible into the polar night, but then enter a "Lazarus mode" until sufficient solar power could be generated in the spring (i.e., turn off until sufficient power is available); or (2) collect observations during the polar night, but not uplink data to an orbital asset until the following spring (note that this plan requires that the spacecraft survive into the spring). However, neither of these types of options has yet been tried in flight and would require ample technology development and demonstration.

5.2 Surviving polar night in mid-latitudes

Surviving the polar night in the mid-latitudes has the same fundamental drivers as the poles but is distinct in some ways. Fundamentally, it is a less extreme problem; as the latitude becomes lower, the interval of polar night decreases, and transitions to low-light conditions rather than permanent darkness. However, the spacecraft's electronics would experience larger and more frequent thermal cycling than a spacecraft at the poles. The minimum temperature (CO_2 frost point) is also roughly the same within all areas that accumulate seasonal CO_2 frost, and thus issues with lubricants and electronics would be expected, as in the polar regions (§5.1).

Additionally, the higher temperatures during portions of the Martian year in the mid-latitudes translate to greater Planetary Protection concerns as induced Special Regions may be possible [Rummel et al., 2014], and mitigation of these concerns may be very expensive (~$100M was earmarked in our Team X landers study for compliance with Planetary Protection processes and procedures). This factor suggests that a non-nuclear power source may be preferable for some mission concepts in the mid-latitudes. Solar power is increasingly viable at lower latitudes but requires large panel areas. For instance, our Team X study estimated that an InSight-class lander at 60°N would require ~11 m^2 solar arrays (approximately double the area on InSight), with tracking capabilities, in order to keep the spacecraft sufficiently warm for survival and to operate (only low-power-need observations) through the low-light seasons and polar night. This constraint might be mitigated by development of better batteries or the use of alternative power sources, as outlined in §5.1. However, as noted above, spacecraft operations with moving parts may have additional issues with lubrication during cold seasons — a consideration for e.g., articulated solar panels or a wind turbine.

5.3 Surface contamination concerns

For many in situ investigations, minimal physical, chemical, and thermal alteration of the area to be investigated (which may include the surface and near-subsurface) is required. This would potentially be a consideration both for landing design and through operations. For example:

- the InSight landing system involves retro-rockets, that can spew propellant onto the surface. (A pathfinder/MER landing system, which utilizes airbags rather than retro-rockets, was thought to be a system that would physically alter the ground less - as the airbags roll to a stop. However, this system also drops material onto the surface, from the rockets as well as the ground it's rolled over.) Such contaminants would obviously be an issue for an investigation including detection of organics, but can also be an issue for climate investigations if a contaminating material alters the local environment/environmental cycles, such as by delaying or preventing the local formation of seasonal frost.
- thermal perturbations, such as that caused by waste heat from an RTG, can impact and potentially negate investigations of the local climate - such as meteorological or frost observations. (A thermal plume directed towards the surface could also potentially erode and destabilize the ground under the lander, if on ice-rich material.) Such heat can potentially also create an induced Special Region under certain conditions, thus raising planetary protection concerns (also discussed in §5.2).

Depending on the investigation, such concerns could be mitigated by the specific timing and/or location of the landing. For example, if a lander were to arrive at the surface on top of a seasonal frost layer, at least some of the surface contamination from landing could potentially be removed with the subliming seasonal frost layer - leaving a cleaner summer surface. (Although potentially not all contaminants may be removed.)

Alternatively, it may be best to assume that the landing/lander site is contaminated and find a way to make observations away from that site. This approach is regularly argued for in making meteorological observations [e.g., Lenoir et al., 2010], where a boom is used to take the instruments away from perturbations induced by the main body of the spacecraft. For meteorological observations, a boom should have length on the scale of the spacecraft body (usually ~1 meter), or longer. For measurements that cannot be completed on the end of a boom/arm, or that need to be made further away from the lander (e.g., contamination extends over a larger area), perhaps a small rover could be used to make the measurement or at least collect the sample; this approach has been considered for life-detection investigations, where it is thought to be potentially much easier to sterilize a small sample collector instead of the full spacecraft.

5.4 Landing on the poles during specific times of year

Some of our science investigations required landing in the NPLD during a specific portion of the year (for instance landing in mid-spring, after peak seasonal frost accumulation has finished). The Team X study identified when during a Mars year one could land at 60°N or 82°N (any longitude), for launch opportunities between 2026 (the earliest it seemed reasonable to launch a new mission) through 2035, using a ballistic trajectory similar to other Mars landers. Figure 5.1 shows the range of L_s values when landing is achievable at the specified latitude using Hohmann transfers of Type I/II (~1/2 revolution around the sun, 0.5–1 Earth years transfer time) and Type III/IV (~1.5 revolutions, 1.5–2 Earth years transfer time). The longer Type III/IV transfers have not been used by any previous Mars landers but offer better north pole accessibility and seasonal advantages in some opportunities. For instance, there is no valid Type I/II transfer to 82°N in 2026 or 2028, but there are valid Type III/IV transfers in those years.

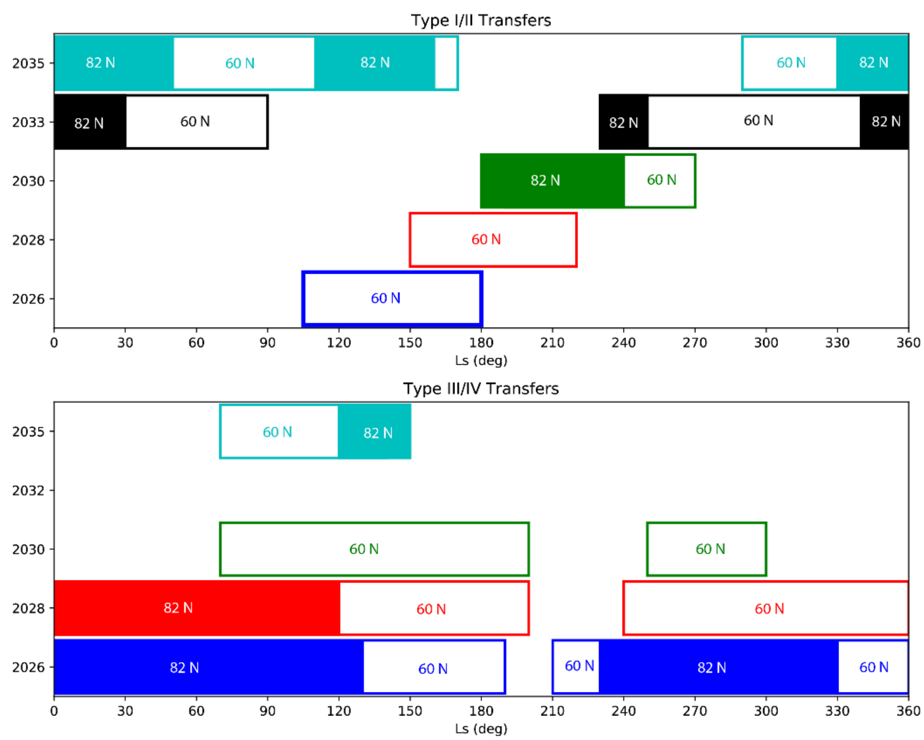


***Figure 5.2**. Plots show approximate L_s-periods with accessibility to landing sites at a given latitude, via ballistic trajectory from 2026 to 2035. Illustrated are estimated periods within the Martian year (expressed in L_s) when a spacecraft can land at a site at 82°N (solid) or 60°N (hollow + solid), assuming a launch capability of 50 km^2/s^2 (roughly an Atlas V 411 launching InSight-like mass) and an entry velocity of 7.5 km/s (in family with previous Mars landers) for several launch opportunities. The y-axis is the launch opportunity year (also denoted with the colors of the bars). Note that these are guidelines from a preliminary study and detailed trajectory designs have not yet been performed, so L_s accessibility should not be assumed for a specific mission concept. Interpolation or extrapolation is discouraged, as the relationship between latitude accessibility and L_s is highly non-linear. The top plot shows Type I/II Hohmann transfers = cruise time is ~0.5–1 Earth years and occurs through ~1/2 revolution around the sun; the bottom plot shows Types III/IV Hohmann transfers = cruise time ~1.5–2 Earth years as the cruise and occurs through ~1.5 revolutions.*

These access limitations could be mitigated through using solar electric propulsion (SEP). SEP has been widely adopted in the communication satellite industry, with over 200 satellites flying with this technology onboard. Several flown interplanetary missions, including Dawn [Brophy, 2011], Hayabusa, Hayabusa 2, and Bepi Colombo, have used this technology to enable them to reach their respective destinations. SEP offers significantly increased delta V capability due to its high specific impulse, which can in turn enable other mission benefits such as increased delivered mass or adjusted arrival conditions (including arrival season, lighting, latitude accessibility, or entry velocity). Utilizing SEP on the cruise stage was not specifically considered in this study, but is it noted that SEP technology is becoming more cost effective and may be an affordable mission enabler for concepts with specific arrival constraints.

5.5 Accessing the Subsurface

Sample acquisition, manipulation and analysis is universally recognized as one of the greatest challenges for in situ exploration of planetary subsurfaces, whether composed of rock, ice, or a mixture of both. In addition to embedded dust, CO_2 and H_2O ice deposition in fine layers often include trapped gas bubbles representing atmospheric composition at the time of entrapment whose analysis becomes an important part of the record of planetary evolution. Examples of the challenge of sample acquisition include the failure of the Phoenix lander to ingest scooped ice for isotopic analysis and more recently the struggles of the InSight lander percussive drill (mole) to reach depth after hitting a rock. The success of the ExoMars Schiaparelli lander's drill is yet to be assessed (Fig. 5.2). Regions of deep ice deposit (CO_2 and/or H_2O ice, such as at the NPLD region) present a more homogeneous and predictable drilling approach, and two approaches have emerged: mechanical drilling, and thermal probe melting.

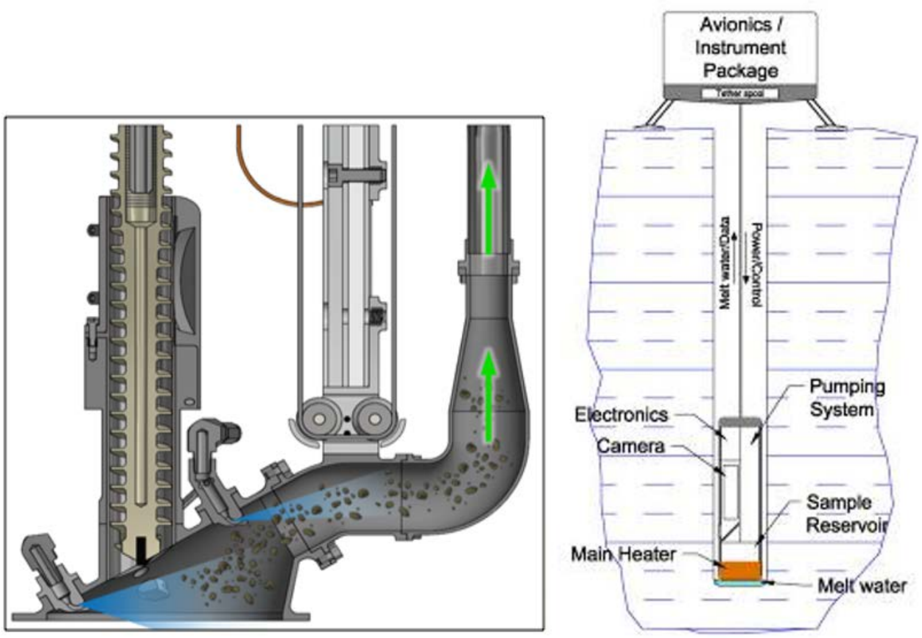
Before discussing the trades between mechanical drilling and thermal probe melting, we must first recognize that mission science objectives require that the integrity of vertical layers (microns to millimeters thickness) laid down over the years must be preserved and sampled on a similarly fine vertical scale. This must be done by either sampling in situ within the "borehole", or by transporting the collected sample up to the lander above. Both have their challenges in preserving the integrity (physical, vertical scale, chemical) of the samples. For water isotope analysis (e.g., recording the D/H or $^{18}O/^{16}O$ ratios of layers to reveal the climate record) using tunable laser techniques, vapor samples are required to allow production of high-resolution spectra. Isotopic analysis therefore requires water vapor production within the borehole itself for in situ laser probing. Alternatively, ice crystals, liquid melt, or vapor must be sequentially extracted at the site and sent up to the surface for analysis. Both have challenges: the former in situ approach requires micro-instrumentation of high measurement capability, whereas the latter surface transportation approach must maintain sample integrity and record without memory effects.

Drill depths of a few meters can be readily achieved for mechanical drills, and up to ~100 m for thermal probes. With precise spatial depth resolution, even a 1-m depth should reveal the last ~1,000 years of climate record within a single obliquity cycle. Shown in Fig. 3.5 is the kind of data we might expect to see for H_2O and CO_2 isotopes and dust if we could sample the NPLD vertical ice record at high-resolution. Mechanical drills that include percussive or hammering capabilities have been developed for Earth climate record ice core collection; with the right "bit" such drills are a relatively fast method of making a clean coring into ice deposits while maintaining the borehole/ core vertical structure. On Earth, drill depths of up to 4 km have been achieved for polar ice cores, but for planetary bodies, a limit of a few meters for the first mission is thought a feasible aim with mechanical drilling (Fig. 5.3).

Other drilling methods, though, may present advantages. For example, Honeybee Robotics presented to ICE-SAG about a recently developed method of drilling using a compressed gas mechanism to eject a sample and deliver it to the surface for analysis (Fig. 5.4). This type of approach appears to offer a low power method for sequentially acquiring microsamples with depth and could be applied to a variety of material compositions.

(Right) ***Figure 5.3.*** *Artistic representation of the ExoMars Schiaparelli drill, deployed on Mars. This drill has a 1 cm diameter and is designed for up to 2 m depth, although in a rocky environment. (Image credit ESA).*

(Below) ***Figure 5.4.*** *Schematic illustrations of drill concepts proposed for operation on Mars.* Left: *Schematic of the Honeybee pneumatic sample delivery mechanism.* Right: *Schematic of a heated probe concept, developed by Hecht et al. [2006] and proposed under the Mars Scout program. This concept has since been field-tested in Greenland. (Figures used with permission from K. Zacny, Honeybee Robotics and M. Hecht, MIT.)*



Although the mission concepts focused on within ICE-SAG focused on drilling only ~1 m in depth, information was also sought on drilling methods that could allow for deeper penetration. For example, the record of a single obliquity cycle of 50–120 kyr may extend through >40 m of vertical deposition [e.g., Milkovich & Head, 2005; Smith et al., 2016], so analysis over depths of

~100 m or more would be needed for detailed analysis of the recent climate record (§3.3.1). ICE-SAG was made aware of a thermal probe concept, where a descending probe, with an internal in situ payload, slowly melts its way down through the ice layers, analyzing samples along its way (Fig. 5.4). The heated tether supplies power, removes water to the surface, and records data. A 7.5 cm-diameter thermal probe prototype has been built [Hecht & Carsey, 2005] and successfully penetrated 40 m into Greenland ice, with engineering parameters (power, speed etc.) that show its potential suitability for Martian ice core sampling. Although requiring about 100 W to travel continuously, the thermal probe descends quite quickly (~10 cm/hour) to minimize total energy requirements. Payloads for a thermal probe have been suggested in prior NASA proposals such as the Mars Scout CHRONOS (Hecht et al. 2006) that included miniature instruments travelling down a borehole whose diameter was several centimeters. In addition to a tunable laser spectrometer, a microscope camera is included to record layering and the density of dust particle layers intertwined within the ice deposition records. The stratigraphic profile would have included temperature, dust density, oxygen isotope fractionation, pH, conductivity, and redox potential.

For both mechanical and thermal drill approaches, sample integrity is critical, which presents the difficult challenge of contamination avoidance. Contamination can be physical (memory affects, mixing of sample layers, mixing or transportation of dust within melted layers) or chemical (oxygen isotopic exchange between liquid water and sublimed CO_2 gas) so that clear mission-specific contamination level requirements must be stated that designs meet with margin.

Despite the encouraging progress made with mechanical drills and thermal probes, this technology as applied to sampling of planetary icy surfaces is in its infancy. Further investment to develop both penetration and sampling technologies would benefit missions to the icy moons of the outer planets, as well as to studies of the Martian cryosphere.

5.6 Lower-cost Access to the Martian Surface

During ICE-SAG discussions with the JPL Team X and MPO engineers, mission concept cost estimates suggested a general inability to do a targeted, “soft” Mars landing with a medium-to-large landed spacecraft for under ~$500M. Although the estimations discussed within ICE-SAG were very rough and the exact cost estimates for these types of mission concepts may be debated, the point stands that landing on Mars can be expensive.

To lower the cost of surface access, one can consider some combination of a smaller landed mass, relaxed landing accuracy constraints, or allowance for a harder landing. Towards these ends, ongoing engineering efforts aim to identify landing systems capable of semi-hard landings in rough terrain without the use of retrorockets or airbags (which would presumably cover the immediate landing site). For example, the $Mars_{DROP}$ concept in development at JPL deploys small probes carrying payloads of ~1 kg or smaller to the surface using a parafoil technology with automated guided descent [Staehle et al., 2015]. By lowering the angle of attack, the parafoil bleeds off and translates momentum to the horizontal direction, reducing g-forces on impact. This type of lander is designed to handle moving through less atmosphere (so as to land at even the higher elevation of the south polar region = ~2–4 km above the areoid), and meter- to decameter scale roughness and steep scarps on the residual polar caps, and would avoid impingement of rocket exhaust or other byproducts of landing that might contaminate the pristine polar ices (§5.3). The lack of a parachute in these designs also means that high uncertainties about the polar wind speeds and directions are less of an issue. A landed Mars mission concept with these characteristics has been discussed for studying the NPLD [Smith, I.B., et al., 2018b].

For the ICE-SAG concept study of small meteorology landers (§4.3), the MPO engineers used a similar concept, but capable of carrying more payload to the Martian surface, for starting costing and capability estimations. The *SHIELD* concept, under development at JPL [Wooley et al., 2018], assumed a 2-m diameter carrier that could bring a ~20 kg payload to the surface; compression upon impact would dissipate energy, reducing landing-forces on the payload (although further engineering would be needed to bring shock-loading to sufficiently low levels for the types of instruments of interest). For the SHIELD concept, the landing ellipse would be quite large (~100 km), but for the studied mission concept, high landing accuracy was not a requirement; also, there may be options for adding guidance and thus reducing the size of the landing ellipse. As with *Mars$_{DROP}$*, the design has the advantages of handling rough terrain, avoiding surface contamination due to rocket exhaust, and being fairly impervious to winds.

More work is needed to develop these types of landing systems. Additionally, development of smaller and more shock-hardened instruments would be highly complementary investments for enabling compelling, focused science investigations to access the Martian surface at a lower cost.

6 Key complementary studies for Ice and Climate focused Mars missions

In this Section, we outline knowledge gaps that came up in ICE-SAG discussions of needed measurements (§3) and mission concept development (§4) that could be addressed by analog studies. Investments in laboratory, modeling, or field studies that would address these gaps would enable or greatly enhance the ability to achieve the measurements needed to answer high-priority Mars ice and climate questions (§3). As will be discussed in this section, ICE-SAG finds the following:

> **ICE-SAG FINDING 16.** Laboratory, modeling, and field studies were identified that would enhance acquisition and interpretation of needed measurements. These include investigations of CO_2 frost evolution, water interaction with Martian regolith, variation of material properties with regolith composition, the relationship between Mars' radiative balance and atmospheric processes at local and regional scales, and analog studies of terrestrial ice cores and climate records.

6.1 Laboratory Investigation of Material Properties of CO2 Ice & Surface Mixtures

Analysis of the remote-sensing data from the Martian polar regions has often been hindered by the lack of experimental measurements of various properties of CO_2 ice and properties of mixtures of CO_2 and H_2O ices with lithics and with each other. Laboratory experiments to constrain thermal, mechanical, geophysical, and EM properties of ice mixtures would aid interpretation of existing data sets as well as design and interpretation of future spacecraft-born investigations.

Electromagnetic propagation characteristics

Observations by MARSIS and SHARAD radar sounding have demonstrated that the transparency of the PLD ice to radar signals equates to dust contamination of order 10 to 15% in the south and as low as 5% in the north [Seu et al., 2007; Plaut et al., 2007; Zuber et al., 2007; Grima et al., 2009]. Spectral modeling of observations by OMEGA and CRISM include ice and non-ice materials in intimate mixture or layered models [e.g., Calvin et al., 2009; Liu et al., 2018]. The grain size of the ice is known to vary with location as well as season [Appere et al., 2011; Langevin et al., 2005; Liu et al., 2018; Pommerol et al., 2011]. In the north a seasonal wave of darkening is related to a dust lag left behind as the seasonal frost retreats, which is later mobilized by wind to result in brightening [Calvin et al., 2015; 2018]. Additionally, the seasonal ice in the north has a water ice collar when the dominating spectroscopic signature of the upper surface transitions from CO_2 to water ice during seasonal sublimation [Appere et al., 2011; Brown et al., 2012]. The albedo of the north residual ice is such that some amount of dust must be included [e.g., Calvin et al., 2009; and as concluded early on by Kieffer et al., 1976]. The complex erosional features in the residual south cap leave slumps of dark material [e.g., Thomas et al., 2005; 2016]. Hence the properties of mixtures of water and CO_2 ices with dust grains is of crucial importance to understanding the nature of these materials in both seasonal and residual ice deposits as well as transparency to radar signals.

Empirical constraints on CO_2 properties are especially important for the observations of the changes in the seasonal northern and southern caps. For example, it has been observed that CO_2 ice density varies through seasons [Matsuo and Heki, 2009]. From experimental and theoretical considerations, it has been hypothesized that sintering, i.e., merging of multiple crystals accompanied by the change of crystalline structure of the CO_2 ice, produces the density variations

[Eluszkiewicz, 1993]. However, the exact limits of the environmental conditions permitting or enhancing the sintering process in the CO_2 ice are unknown and require specific laboratory investigations. Differences in the radiative properties of the different forms of solid CO_2 (frost vs slab ice vs snow) might explain the observed variations in the seasonal cap albedo [Titus, 2007; Pommerol et al., 2011] but they have not yet been measured. More often than not, the optical constants of CO_2 ice that are currently used in the calculations of the energy balance for the seasonal caps were measured at a single temperature value. This restricts the structure of the CO_2 crystal under consideration to the one that forms at the chosen temperature (e.g., 150 K as in Hansen [1997]). In addition, the dependency of IR, visible and UV spectra of CO_2 on grain size is under-explored. The potential presence of H_2O crystals and dust contamination inside the seasonal CO_2 ice layer complicates the problem further. Dust and water inclusions moderate optical properties and heat transfer inside an extended CO_2 ice body produces enhanced ice cracking [Portyankina et al., 2019], modification of the optical properties, and changes to the mechanical stability of the seasonal ice. In other words, cracks in the ice reflect, scatter and direct incoming light and the resulting phase function might deviate greatly from the phase function of snow or continuous slab.

The planetary ice lab in Bern [Pommerol et al., 2011] provides goniometric measurements of ices, but only in the visible and near-infrared up to 1100 nm. Some experiments of CO_2 ice condensation under conditions similar to those expected in the Martian polar areas have also been done [Portyankina et al., 2019]. In addition to laboratory observations of CO_2 ice sintering (with a range of contaminants) under Mars polar night conditions, spectroscopic measurements of ice mixtures with dust and salts at wavelengths up to 4 μm are needed to understand how well current radiative transfer models predict actual spectral properties.

Geophysical and mechanical properties

Observations of the microphysics of CO_2 deposition from direct condensation are needed to understand how porosity or other properties contribute to the erosional morphologies seen in the SPRC. Mechanical properties are a major gap in our knowledge about CO_2 ice. The few existing rheological measurements on CO_2 ice [Durham et al., 2010; 1999] explore its ductile flow behavior, i.e., viscous flow under low-stress conditions and/or over long timescales. The brittle behavior of CO_2 ice is, in contrast, completely unknown. CO_2 ice behavior must be considered in the brittle mode for seasonal applications. Yield stress and Young's modulus of the slab CO_2 ice and of granular ice after sintering have not been measured. Knowing yield stress and Young's modulus for CO_2 ice is important for understanding seasonal activity, particularly for estimating timing of CO_2 layer break-up in spring and the production of cold jet eruptions. Young's modulus is also important for understanding interactions of the seasonal layer with underlying substrate and such processes as formation and modification of gullies on CO_2-covered dunes and crater rims, and initiating avalanches on steep slopes.

Interactions between CO_2 and H_2O during their condensation and sublimation cycles are also underexplored processes. The creation of the lag deposit of H_2O ice left behind after the seasonal CO_2 layer has sublimed potentially leads to the formation of the polar layer deposits. Knowledge about the creation process of this lag is limited and somewhat at odds with observations of the seasonal H_2O annulus [Appere, et al., 2011], which points to simultaneous sublimation of CO_2 and H_2O or at least displacement of H2O ice crystals embedded in sublimating CO_2. More experimental investigations are needed to quantify the amounts of H_2O ice left behind by CO_2 layer sublimation under the variable conditions of local spring in the polar regions.

Thermal properties

Finally, measurements of thermal conductivity for mixed materials at a range of relevant Mars near surface temperatures are needed for input into thermal models (discussed more in §6.3).

6.2 Laboratory Investigation of Water Transfer Through and Interaction with Regolith

A landed mid-latitude mission could provide critical measurements of near-surface H2O, specifically by quantifying H_2O exchange, detecting and quantifying changes in water vapor abundance, detecting liquid or adsorbed water, and characterizing soil mineralogy and changes in hydration state over multiple diurnal cycles and seasons. However, new laboratory studies of H_2O interaction with regolith materials would substantially and independently improve our understanding of H2O exchange between the surface and the atmosphere and the long term effects of this exchange on near-surface materials. These laboratory measurements would also directly aid the design and interpretation of landed experiments. In the shallow subsurface, water molecules can exist as crystalline ice, adsorbate on mineral surfaces, water of hydration in altered minerals and salts, thin films at ice-mineral and ice-ice interfaces, deliquesced salts, and bulk brines. Partitioning of H_2O amongst these reservoirs influences the dynamical behavior of ice and water vapor, and is important in considerations of landscape development and habitability. In addition, salt deliquescence, hydration state changes or thin films can potentially have long term effects on soil chemistry and physical properties, and subsequently on vapor diffusion and ice table evolution. Here we briefly note topic areas where dedicated support of laboratory investigations would complement landed missions to the mid-latitudes, specifically:

Adsorption on regolith grains and mineral hydration

Both orbital and in situ observations have long indicated a diurnal variation in the water vapor abundance in the Martian atmosphere. This "breathing" of the regolith is likely controlled by the adsorptive properties of the regolith grains. Adsorbate abundance and kinetics both influence and are influenced by water vapor diffusion through the soil column. Adsorption isotherms have been measured for a modest range of Mars-relevant soils and gases [e.g., Jänchen et al., 2006; 2009; Pommerol et al., 2009; Zent & Quinn 1995, 1997; Zent et al., 2001], and reveal a range of mineral-specific behaviors. There have been few studies of adsorption kinetics [Beck, et al., 2010], although kinetics may be critical to understanding regolith breathing. Adsorption studies rarely extend to temperatures < 253 K, and currently available empirical data must be extrapolated to the temperatures most relevant to mid- and high-latitude Mars. In the coming decade, landed science would be enhanced by water vapor and CO_2 adsorption experiments that expanded the explored parameter space to a wider range of soils and lower temperatures, with emphasis on the kinetics of adsorption. These experiments could be complimented by coordinated spectroscopic studies [e.g., Beck et al., 2010]. Better understanding of adsorption kinetics might also prompt a revisitation of the molecular diffusion experiments of the late 2000s [Hudson et al., 2007, 2008; Bryson, et al., 2008; Sizemore & Mellon, 2008] with new, more complete considerations of adsorption and salt migration [e. g., Miller et al., 2019] for comparison with in situ observations.

Deliquescence, brines, and premelted water

Deliquescent brines have been invoked to explain the darkening and downslope movement of Recurring Slope Lineae (RSL) and spherules of material at the Phoenix landing site. A variety of focused studies have investigated deliquescence of perchlorates and other salts under Mars-relevant conditions [e.g., Gough et al., 2011; 2014; 2016; Nuding et al., 2014], but these studies have primarily revealed a large and complex parameter space for brine development and salt precipitation on Mars.

Likewise, investigation of the bulk properties and freezing behaviors of perchlorate brines is in its early stages. Brines and brine-soil mixtures exhibit significant hysteresis on freezing and thawing, with substantial unfrozen content at very low temperatures [Toner et al., 2014; Stillman et al., 2019]. Details of these processes are only beginning to be revealed by experiments. Viscosities of bulk, low temperature brines are nearly absent in the literature. New research suggests the properties of bulk and adsorbed brines differ significantly. Similar to brines, liquid films of premelted water can exist at ice-mineral and ice-ice interfaces at temperatures substantially below bulk freezing even in the absence of salts [Dash et al., 2006]. Salts may enhance the volume, mobility, and habitability of premelted liquids [Toner et al., 2014; Sizemore et al., 2015]. These films may play a role in mineral weathering, landscape development, and issues of habitability, but there are major outstanding questions about how commonly they occur, how significant their volume is in the Martian environment, and how they may affect remote sensing data [e.g., Stillman & Grimm, 2011; Stillman et al., 2019].

An expansion of all laboratory work relevant to low temperature liquids should continue in the next decade. Inclusion of a broader range of salts, salt regolith mixtures, and lower temperatures (<220 K) would be a major benefit to both landed and orbital investigations of martian volatiles.

6.3 Models of Radiative Balance and Climate Cycles

The acquisition of the new empirical data described in §6.1 and §6.3 would facilitate -- and likely necessitate -- the development of new numerical models of surface atmosphere interactions. Completely characterizing the polar energy balance and especially its temporal changes in response to seasons is a key point for understanding the climate system of the whole planet and a starting point to developing a weather forecast systems for future exploration needs. The energy balance (or budget) controls the condensation and sublimation rates. The main components are energy absorbed (solar insolation, thermal conduction from a warm regolith, and downwelling radiation from the atmosphere) and energy loss (thermal radiation to space and thermal conduction to a cold regolith).

Top of the atmosphere.

Orbital remote sensing measures radiative energy at the top of the atmosphere. There are two components: net reflected solar radiation and net emission of thermal radiation. The measurement of the net reflected solar insolation constrains how much of the solar insolation is absorbed by surface material and the atmosphere. The measurement of thermal emission constrains the energy loss to the system (i.e., lost to space). While the net energy balance is mostly the latent heat of fusion, there are other sources that can store and re-release energy that must also be considered - primarily effects from the atmosphere and the near surface regolith. To fully model the condensation and sublimation of CO_2 using radiative balance, these other effects must be included in numerical models.

Effects from the regolith.

The regolith can have a significant impact on the CO_2 energy budget, especially if a large fraction of the near surface contains H_2O ice. H_2O has a very high thermal inertia and acts as a thermal capacitor — storing heat up in the summer and releasing that heat in the autumn. This storage of heat results in basal sublimation of the accumulating CO_2 frost in the autumn, which reduces the net accumulation of CO_2 frost [Haberle et al., 2008; Vincendon et al., 2010] and may be responsible for the appearance of vents (evidence for CO_2 gas jets) that appear before polar sunrise [Aharonson 2004]. Directly measuring the heat storage of the regolith is extremely difficult from orbit. Thermal models, combined with observed thermal physical properties, are currently the best approach. Such models have been used with success for thermal inertia studies, and now turning their attention towards predicting the effects on the net accumulation of seasonal CO_2 ice would be beneficial for present and past ice accumulation studies, as well as providing a basis of comparison against models of CO_2-driven surface activity (§2.4.3).

Currently used thermal models [e.g., Kieffer 2013] are generally sufficient for these types of studies, especially with many of them now including the effects of far-field surfaces (differing temperatures of topographical surfaces that are within view of the surface of interest). However, in situ measurements of thermal physical properties and real-time heat conduction could provide added constraints to current modeling efforts; more realistic input parameters and material characteristics would yield the largest improvement in these studies (§6.1).

Lateral transport of heat within the atmosphere

Mars' energy balance is affected by the lateral (meridional) transport of heat by the atmosphere. Heat transported into the polar regions from the lower latitudes affects CO_2 condensation, particularly near the edges of the growing and receding seasonal caps [Kahre & Haberle, 2010]. Direct measurement of the lateral heat transport, (and the decomposition of that transport into various components: mean, eddy) requires concomitant observations of the thermal and wind fields.

Effects of dust

Dust plays a critical role in the current climate of Mars, but the dust cycle itself has been very challenging to reasonably simulate with climate models. In particular, simulating the observed variability in dust storm behavior (particularly the interannual variability of global dust storms) has been elusive. Continued studies are needed that focus on the role of finite surface dust reservoirs and the coupling of the dust and water cycles through cloud formation. Understanding how the dust cycle has evolved over time will require fully coupled, interactive dust cycle modeling studies under different orbital configurations. Fully interactive, coupled modeling studies would allow for the prediction of polar (and non-polar) dust deposition, which will be needed for understanding how and when polar layers are formed.

Effects of active clouds.

Clouds can either warm or cool the climate system. The net effect of clouds on the climate system depends on cloud optical depths, altitudes, and particle sizes. Our current understanding of the effects of clouds on the climate system come from models. For example, models indicate that clouds do not provide significant net annual mean warming or cooling on current day Mars, but water ice clouds have been shown to critically impact the general circulation [Barnes et al., 2017]. Models predict that clouds may have had an even larger effect on the climate system throughout Mars' history.

In turn, cloud formation mechanisms are a major unknown in the Martian climate studies. The microphysics of water and CO_2 nucleation requires a highly complex theoretical description in terrestrial investigations; under the low temperature/low pressure environments of the upper Martian atmosphere these microphysics are even less understood. In addition, most studies on modeling the formation of Martian clouds have focused on describing only either CO_2 or H_2O clouds, but the two components can theoretically condense together as a clathrate or an eutectic mixture of CO_2 ice with clathrate or H_2O ice [Määttänen et al., 2007] and it not known how important inclusion of these more complicated cloud formations may be within Martian climate modeling. Additional detailed modeling studies (constrained by available observations) with increased spatial resolution and improved representation of microphysical processes are needed to fully understand how clouds affect the current and past Martian climate system.

6.4 Field analog work to support investigation of Martian ice layers

Dust plays an important role in the Martian climate system as it carries heat and interacts with atmospheric water vapor transport and processes. Dust storms move dust from low-latitude source areas towards the poles, where dust deposits build up over icy surfaces. Although the importance of ice-dust interactions are well recognized, the effects on energy and water fluxes are not well constrained. In addition to lab work discussed in §6.1 and §6.2, terrestrial field studies of the effects of dust on natural ice surfaces are critical in establishing realistic relationships between dust concentration, albedo and erosion. Studies of the effects of volcanic ash on icelandic glaciers show that deposition of dust on a glacier can significantly change the mass balance of the glacier. Debris can increase the glacial melt due to changes in albedo, or it can cause insulation effects [Dragosics et al., 2016]. The effect of dust on bare ice is much more significant than on snow [Box et al., 2012]. Field studies should consider ice grain size, dust particle size and shape, and effects of salts; doing so would likely advance the ability to interpret remote sensing data.

Both sublimation of water ice and deposition of frost and dust at the surface have contributed to layer formation in the Martian climate record. Bulk precipitation has also likely played an important role at certain times and locations. Over time, surface frost or snow turns into firn (intermediate stages) and finally ice. On terrestrial glaciers the snow compaction process (densification) depends on the concentration and composition of impurities [Hörhold et al., 2012], and occurs over depths ranging from >100 m in the cold and dry climate in Antarctica to few meters depth when melt water is present. Observing and quantifying this process and its dependence on terrestrial climate and atmospheric dust content is important to understanding layer formation on Mars (§3.4). Field studies of this type could also directly inform the design of in situ spacecraft investigations.

The subsurface stratigraphy of Martian ice layers has been mapped with two orbital sounding radars (§2.1 and §3.3). Similar techniques are used to map the stratigraphy of terrestrial glaciers and ice sheets. Detection of reflectors indicates variations in the dielectric properties of subsurface ice, due to changes in density, or dust or impurity content, for example. On Earth, radargrams can be compared directly to ice core records nearby. The brightness of a given reflector may imply the presence of liquid water. For example, a bright reflector could be produced by melt at the bottom of a large ice sheet, due to the dielectric contrast liquid water provides against rocky materials. Understanding the relationship between radar reflectors and the composition of the corresponding ice layers is crucial for interpreting the basal thermal state of terrestrial ice sheets [e.g., MacGregor et al., 2016]. The recent interpretation of a bright radar reflector in the Martian southern hemisphere as evidence of liquid water [Orosei et al., 2018] underscores the importance of understanding how radar propagation is affected by the phase partitioning in subsurface ice deposits. Studies of the Greenland radar stratigraphy show that ice originating from the last glacial maximum is an echo-free zone, perhaps due to the high dust content during that period (Fig 2.1). This highlights the need for terrestrial studies to better enable analogous interpretation of Martian radar data as indicators of layer thicknesses and properties (§3.2 and §3.3).

7. Conclusion

In this report, we have presented 16 key findings from the ICE-SAG, which summarize our main conclusions about the key outstanding questions related to the Martian ice and climate system, possible mission concepts that could address subsets of these questions, and additional areas of technology and study investment that would enhance feasibility of the mission concepts.

Additionally, we summarize here how the mission concepts, identified by ICE-SAG as feasible within the next decade, would each address high-priority Mars ice and climate science. As shown in Tables 7.1 and 7.2, all of the mission concepts address at least one of the ICE-SAG Priority Science Areas (§3) and at least one of the highest-priority questions and measurements, with the New Frontier cost-class missions each addressing several highest priority questions and measurements. While no individual mission addresses all areas of investigation needed to understand the full "records" left by Mars climate history, each would contribute significantly in a particular area towards a quantitative understanding of Mars' climate states and shifts over the last few million to billions of years.

Each of such missions would yield important information not only for all studies of Mars, but also for our understanding of climate states and evolution, and how that climate may be recorded, within terrestrial worlds. This would provide important comparative planetology data against our knowledge of the Earth's climate and climate records, and would add to the broader understanding of climates that may be found within extrasolar worlds.

The previous Decadal Survey, *Visions and Voyages*, recognized the importance of planetary climatological investigations, stating:

> *"Mars has perhaps the most Earth-like modern planetary atmosphere, and its earliest climate may have been very Earth-like. Studying it therefore provides opportunities to validate terrestrial climate and global circulation models under very different atmospheric conditions. Mars's polar layered deposits suggest climate change in the last 10 million years, and dynamical models predict large recent excursions in axial tilt and orbital eccentricity. These considerations point to recent climatic change, analogous to ice ages on Earth, detailed records of which are likely preserved in the polar layered deposits. ... The continued investigation of Mars's climate through time and the study of its modern atmospheric processes from orbit, from the surface, and ultimately from analysis of returned samples conditions remain high priority scientific objectives."* [V&V, 2011: p3-14]

Visions and Voyages went on to discuss the Martian climate drivers and icy deposits extensively within the set of Mars key science questions (related to both the *Processes and History of Climate* and *Evolution of the Surface and Exterior*). Based on recent science discoveries, Mars ice- and climate-science questions have been refined and focused, enabling the science community to extract more value from addressing key science or measurement gaps. Thus, the related investigations described in *Visions and Voyages* have become even more compelling. Furthermore, based on new and expected technology development, it now appears more feasible to address these investigations, with an array of options over a broad range of mission-cost classes.

In conclusion, ICE-SAG looks forward to the next decade, during which we encourage NASA to address as many of these Priority Science Areas as may be feasible. Achieving these goals would greatly advance our understanding of the processes of volatile transport and layer formation and our knowledge of the locations and types of volatile reservoirs, effectively producing a Rosetta Stone needed to begin decoding the records of the Martian climate.

Table 7.1. *The science questions within the Priority Science Areas (§3) addressed by the mission concepts described within this report (§4), with the highest-priority questions listed individually. NF = New Frontiers-cost class, SS = Small Spacecraft.*

QUESTIONS	NF1	NF2	NF3	NF4	NF5	SS1	SS2	SS3
Priority Area A: atmos transport of materials	x	x	x	x	x		x	x
Q1: atmos controlled exchange, global/vert			x	x				x
Q4: mass flux volatiles			x	x	x			x
Q6: rates ice/dust on res caps	x	x	x				x	
Priority Area B: distr/volume of water ice				x	x			
Q8: subsurf water ice location/depth				x	x			
Q9: subsurf water ice volume/purity				x	x			
Priority Area C: vert structure ice reservoirs	x			x	x			
Q16: constituents in layered ice	x							
Priority Area D: surface activity and conditions	x	x					x	
Q19: layer formation processes	x	x					x	
Priority Area E: evidence of liquid water				x	x	x		

Table 7.2. *The measurements needed to address the science questions within the Priority Science Areas (§3) addressed by the mission concepts described within this report (§4), with the highest-priority measurements listed individually.*

MEASUREMENTS	NF1	NF2	NF3	NF4	NF5	SS1	SS2	SS3
Priority Area A: atmos transport of materials	x	x	x	x			x	x
M1: wind global/PBL			x					
M2: water, dust, temp, press global/PBL			x					x
Priority Area B: distr/volume of water ice				x	x			
M6: map global near-surf structure					x			
Priority Area C: vert structure ice reservoirs	x			x	x			
M12: characterize layered material	x			x				
Priority Area D: surf activity & conditions	x	x					x	
M16: surface met conditions	x	x					x	
Priority Area E: evidence of liquid water				x	x	x		

8. Acknowledgements

ICE-SAG thanks our subject-matter experts, JPL's Team X engineers, other external contributors, and our reviewers for very helpful and informative inputs to our discussions and report. We also thank the Planetary Science Institute (PSI), Kimberly Foote (PSI), and Barbara Saltzberg (JPL) for hosting and supporting our January 2019 meeting in Tucson; and Kelly Perry (JPL) and Tommy Thompson (JPL) for their assistance with telecons and report references. The work completed by JPLers (Diniega, Mischna, Tamppari, Webster, Thompson, and Perry) was carried out at the Jet Propulsion Laboratory, California Institute of Technology; this work and travel by ICE-SAG members to the Tucson meeting were supported by the Mars Program Office, Jet Propulsion Laboratory, under a contract with the National Aeronautics and Space Administration.

Appendix A: ICE-SAG Charter

Mars Exploration Program Analysis Group (MEPAG)
Science Analysis Group Charter
Ice and Climate Evolution Science Analysis Group (ICE-SAG)

Purpose

As part of community preparations before the next Planetary Science Decadal Survey, the MEPAG Executive Committee seeks to explore approaches to answering the fundamental science questions in its MEPAG Goals Document. A recent update to that document incorporated changes focused on polar science and the ongoing evolution of Mars volatiles and climate. Formation of the ICE-SAG is meant to identify what might be done in the coming decade (2023–2032) to achieve compelling science objectives on this topic and to guide future Mars missions.

Background

Orbital and in situ surface exploration of Mars have revealed a complex system of ice deposits on the planet:

- Permanent polar caps with icy layered terrains, which are thought to contain records of the Martian climate over the geologically recent past, but whose apparent age and internal layering differ dramatically between north and south poles.
- Possible detection of a briny lake beneath a mile of south polar cap ice.
- Enough carbon-dioxide ice sequestered in the south polar cap that, if sublimed, would more than double the present atmospheric mass.
- Ice in the uppermost meter or two of the ground at latitudes extending from the poles into mid-latitudes, where some small impactors have exposed shallow ice closer to tropical latitudes.
- Massive ice in the form of debris-covered glaciers in numerous mid-latitude locations.
- Evidence that seasonal carbon-dioxide frost may be a major surface erosive agent at mid-to-high latitudes on the planet within the present climate.

Hypotheses for the formation of these deposits, together with adjacent landforms, point to the effect of the transport, deposition, and sublimation of volatiles over seasonal, interannual, and ultimately much longer timescales, i.e., those of the Martian astronomical cycles (periodic variations in obliquity of the rotation axis and in the eccentricity and phasing of the orbit). However, much remains to be learned in confirming these hypotheses and even being sure that the critical processes are fully identified and quantified. For example, even today we do not know if either of the polar caps are undergoing net accumulation or erosion or how to interpret the different observations of layered deposits that are seen as records of “recent” past climates and climate shifts.

Quantification of the placement and movement of Martian volatiles is needed to understand volatile processes and their distribution over Mars through geologically recent history. That volatile history has implications for geochemical and astrobiological studies, as well. While this charter focuses on potential science gains, an understanding of volatile distribution and of dust properties also has implications for planning activities by humans working on the Martian surface. Thus, investigations within all four MEPAG goals may come into play in this study.

ICE-SAG Guidelines

With this charter, the MEPAG Executive Committee forms the ***Ice & Climate Evolution Science Analysis Group (ICE-SAG)*** to explore approaches to address the fundamental science questions related to the recent and ongoing evolution of Mars volatiles and climate in the coming decade. The ICE-SAG would identify:

- Compelling science objectives that could be addressed in the next decade (2023–2032), with traceability to the recently updated MEPAG science Goals (Life, Climate, Geology).
- Measurements required to address these objectives and proof-of-concept techniques needed to make these measurements, and/or the technology investments needed to develop the required techniques to a sufficient level of maturity.
    - Include a traceability matrix linking these measurements to the 4 MEPAG goals: Life, Climate, Geology/Geophysics, Preparation for Humans
- Mission approaches—including orbiters, landers, drillers, rovers, networks—that could address the compelling science objectives and make the required measurements.
    - This assessment includes identifying possible linkages between missions and measurements, and indicating which are needed before others and which are needed concurrently.
    - Identify the major technical challenges (e.g., operations in the polar night).
    - By analogy and comparison, sort the various mission scenarios into the following mission classes: Small Satellite, Discovery, New Frontiers, Flagship.
    - Prioritize the New Frontiers and Flagship class missions for possible costing and technical evaluation (CATE) by NASA in preparation for consideration in the next Planetary Decadal Survey for 2023-2032. (NASA may accept only one candidate for study.)

Approach

The SAG shall take into account the following:

- Recent discoveries in polar and non-polar locales relevant for studies of Martian volatiles and climate, such as those relating to the distribution of ice today and the processes that have produced that distribution in the late Amazonian period.
- Recent updates to the MEPAG Goals Document, which reflect those discoveries.
- The NEX-SAG report: Review the science goals, measurement approaches, and proof-of-concept payloads recommended for that orbiter and modify/focus as appropriate.
- Appropriate inputs from conferences such as the Mars Workshop on Amazonian and Present Day Climate and 6th International Mars Conference on Polar Science & Exploration (incl. special issue) and from previous study groups, e.g., Keck workshops "Unlocking the Climate Record Stored within Mars' Polar Layered Deposits," I and II and "MarsX: Mars Subsurface Exploration".
- Consider expected contributions to volatile/climate science studies from ongoing/current/upcoming missions (TGO, EMM Hope, MRO, ODY, MEx, MSL, etc.).

Methods

- ICE-SAG will conduct its business primarily via telecons, e-mail, and/or web-based processes. Up to two face-to-face meetings may be accommodated, if needed.
- When added expertise is needed, ICE-SAG will request a briefing from a recognized subject-matter expert.
- The MPO's Science Office will provide logistical support.

Schedule and Deliverables

- ICE-SAG will form and begin its discussions as soon as possible.
- A progress report to be reviewed by the MEPAG Executive Committee is requested by mid-December, 2018.
- A final report, text formatted, and a PowerPoint briefing package suitable for presentation to SMD/MEP is requested by 28 February, 2019.
    - The report must not contain any material that is ITAR-sensitive.
    - After the report has been shared with NASA and accepted by MEPAG's Executive Committee, it will be posted on the MEPAG publicly accessible website.
    - A presentation of the SAG results at a MEPAG meeting and at LPSC 2019 would then follow.

Accepted by Jeff Johnson, MEPAG Chair and MEPAG Executive Committee – October 12, 2018

Appendix B: Other Contributors

Subject Matter Experts and Meeting Reports

NAME	INSTITUTION	TOPIC
Rich Zurek & Bruce Campbell	JPL & Smithsonian	NEX-SAG report
Portyankina/Dundas/Mischna/Oehler*		Late Mars workshop
Isaac Smith	PSI and York U	Mars Polar Science conference Amazonian Climate workshop
Vlada Stamenkovic	JPL	KISS MarsX Subsurface workshop
Hayne, Byrne, Smith*		KISS North Polar Science workshop
Kris Zacny	Honeybee Robotics	Subsurface access concepts
Tyler Jones	UC Colorado	Terrestrial isotopic records in ice
Franck Montmessin	LATMOS, IPSL	Martian isotopic records in atmosphere/ice
Jen Eigenbrode	NASA Ames	Astrobiology investigations in ice
Lisa Pratt & Andy Spry	NASA PP Office	Planetary Protections concerns
Don Banfield & Chris Eckert	Cornell U & MIT	Wind-generated power concept
Don Banfield	Cornell U	InSight meteorological measurements
Mike Hecht	MIT	Heated drill concept
Ryan Stephan	NASA PESTO	Planned NASA technology development

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Appendix C: Full list of Ice and Recent Climate Science Questions considered within ICE-SAG

See separate document, linked on https://mepag.jpl.nasa.gov/reports.cfm?expand=topical

Appendix D: Specific MEPAG Goals connected to ICE-SAG Priority Science Areas

Text is taken from MEPAG [2018]: https://mepag.jpl.nasa.gov/reports.cfm?expand=science

Goal 1/Life	**B. Determine if environments with high potential for current habitability & expression of biosignatures contain evidence of extant life.**	**B1.** Identify environments that are presently habitable, & characterize conditions & processes that may influence the nature or degree of habitability therein.	1. Identify areas where liquid water (including brines) presently exists, with emphasis on reservoirs that are relatively extensive in space & time.
			2. Identify areas where liquid water (including brines) may have existed at or near the surface in the relatively recent past including periods of significant different obliquity.
			3. Establish general geological context (such as rock-hosted aquifer or sub-ice reservoir; host rock type).
		B2. Assess the potential of specific conditions & processes to affect the expression and/or degradation of signatures of extant life.	1. Evaluate the physicochemical conditions & processes of surface regolith or rock environments in terms of their potential for preserving or degrading biosignatures, & the effects of these conditions & processes on specific types of potential biosignatures.
			2. Evaluate the potential rate of physical degradation from processes such as wind abrasion, dust storms, dust devils, & frost action.
Goal II/Climate	**A. Characterize the state of the present climate of Mars' atmosphere & surrounding plasma environment, & the underlying processes, under the current orbital configuration.**	**A1.** Constrain the processes that control the present distributions of dust, water, & carbon dioxide in the lower atmosphere, at daily, seasonal & multi-annual timescales.	1. Measure the state & variability of the lower atmosphere from turbulent scales to global scales.
			2: Characterize dust & other aerosols, water vapor & carbon dioxide & their clouds in the lower atmosphere.
			3: Measure the forcings that control the dynamics & thermal structure of the lower atmosphere
		A4. Constrain the processes by which volatiles & dust exchange between surface & atmospheric reservoirs.	1. Characterize the fluxes & sources of dust & volatiles between surface & atmospheric reservoirs.
			2. Determine how the processes exchanging volatiles & dust between surface & atmospheric reservoirs have affected the present horiz. & vert. distrib. of surface & subsurface water & CO_2 ice.
			3. Determine the energy & mass balance of the surface volatile reservoir over relevant timescales, & characterize their fluxes.
	B. Characterize the history of Mars'	**B1.** Determine how the chemical composition & mass	1. Measure isotopic composition of gases trapped in the Polar Layered Deposits (PLD) & near-surface ice.

	climate in the recent past, & the underlying processes, under different orbital configurations.	of the atmosphere has changed in the recent past.	2. Determine how & when the buried CO2 ice reservoirs at the south pole formed.
		B2. Determine the climate record of the recent past that is expressed in geological, glaciological, & mineralogical features of the polar regions.	1. Determine the vertical & horizontal variations of composition & physical properties of the materials forming the PLD.
			2. Determine the absolute ages of the layers of the PLD.
			3. Determine which atmospheric & surface processes are recorded during layer formation.
			4. Constrain Mars' polar & global climate history by characterizing & interpreting the relationships between orbitally forced climate parameters & the layer properties of the PLD.
		B3. Determine the record of the climate of the recent past that is expressed in geological & mineralogical features of low- & mid-latitudes.	1. Characterize the locations, composition, & structure of low & mid-latitude ice & volatile reservoirs at the surface & near-surface.
			2. Determine the conditions under which low- & mid-latitude volatile reservoirs accumulated & persisted until the present day, & ascertain their relative & absolute ages.
	C. Characterize Mars' ancient climate & underlying processes.	**C2.** Find & interpret physical & chemical records of past climates & factors that affect climate.	3. Determine boundary conditions necessary for climate modeling, including topography, state of polar caps, & state of the magnetic field.
Goal III/Geology	**A. Document the geologic record preserved in the crust & investigate the processes that have created & modified that record.**	**A1.** Identify & characterize past & present geologic environments & processes relevant to the crust.	1. Determine the role of water & other processes in the sediment cycle.
			4. Identify ice-related processes & characterize when & how they have modified the Martian surface.
			6. Determine the processes that create dust & distribute it around the planet, identify its sources, & fully characterize its composition & properties.
		A3. Identify & characterize processes that are actively shaping the present-day surface of Mars.	1. Identify present-day changes within the rocky or icy surfaces of Mars, & estimate past & present rates of change.
			2. Determine relevant surface & atmospheric environmental conditions and/or processes that cause observable surficial changes over diurnal, seasonal, & multi-annual timescales.
			3. Extend the evolving knowledge of active surface processes to other locations on the planet & backward in time.

		A4. Constrain the magnitude, nature, timing, & origin of past planet-wide climate change.	2. Characterize surface-atmosphere interactions as recorded by aeolian, glacial/periglacial, fluvial, lacustrine, chemical & mechanical erosion, cratering & other processes.
			3. Determine the present state, 3-dimensional distribution, & cycling of water on Mars including the cryosphere & possible deep aquifers.
Goal IV/Prepare For Humans	**A. Obtain knowledge of Mars sufficient to design & implement a human mission to Mars orbit with acceptable cost, risk, & performance.**	**A1.** Determine the aspects of the atmospheric state that affect aerocapture & aerobreaking for human-scale missions at Mars.	1. At all local times, make long-term (> 5 Mars years) observations of the global atmospheric temperature field from the surface to ~80 km.
			2. At all local times, make long-term global measurements of the vertical profile of aerosols between the surface & >60 km.
			3. Make long-term observations of global winds & wind direction at all local times over altitudes 15 to >60 km, & including a planetary scale dust event.
	B. Obtain knowledge of Mars sufficient to design & implement a human mission to the Martian surface with acceptable cost, risk, & performance.	**B1.** Determine the aspects of the atmospheric state that affect Entry, Descent, & Landing (EDL) design, or atmospheric electricity that may pose a risk to ascent vehicles, ground systems, & human explorers.	1. Globally monitor the dust & aerosol activity, especially large dust events, to create a long-term dust activity climatology (> 10 Mars years) capturing the frequence of all events & defining the duration, horizontal extent, & evolution of extreme events.
			2. Monitor surface pressure & near surface meterology over various temporal scales (diurnal, seasonal, annual), & if possible in more than one locale.
			3. Make temperature & aerosol profile obs. under dusty conditions (including w/i the core of a global dust storm) from the surface to 20 km (40 km in a great dust storm) with a vert. res. of <5 km.
			4. Profile the near-surface winds (<15 km) in representative regions (e.g., plains, up/down wind of topography, canyons), simultaneous with the global wind observations.
			5. Obtain temperature or profiles from all landed missions between the surface & 20 km.
		B3. Determine the Martian environmental niches that meet the definition of "Special Region."	1. Map the distribution of both naturally occurring Special Regions, & regions with the potential for spacecraft-induced Special Regions, as defined by COSPAR5.

	B5. Assess landing site-related hazards, including those related to safe landing & safe operations (including trafficability) within the possible area to be accessed by elements of a human mission.	2. Determine regolith physical properties & structure, gas permeability of the regolith & the chemistry & mineralogy of the regolith, including ice contents.
D. Obtain knowledge of Mars sufficient to design & implement sustained human presence at the Martian surface with acceptable cost, risk, & performance.	**D1.** Characterize potentially extractable water resources to support ISRU for long-term human needs.	1. Identify a set of candidate water resource deposits that have the potential to be relevant for future human exploration.
		3. Measure the energy required to excavate/drill & extract water the H-bearing material from either shallow water ice or hydrated minerals as appropriate for the resource.

Appendix E: Acronym List

Acronym	Definition
AO	Announcement of Opportunity
APXS	Alpha Particle X-Ray Spectrometer
BU	Basal Unit
CATE	Costing and Technical Evaluation
CCRI	Capacitively Coupled Resistivity Imaging
CReSIS	Center for Remote Sensing of Ice Sheets
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars (instrument on MRO)
CT	Computed Tomography
CTX	Context Camera (instrument on MRO)
DiAL	Differential Absorption LiDAR
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
EDL	Entry, Descent and Landing
EMM	Emirates Mars Mission (aka Hope Mars Mission)
ESA	European Space Agency
ExoMars	Exobiology on Mars (ESA mission)
FU	Freie Universitat (Berlin)
FY	Fiscal Year
GCM	General Circulation Model
GPR	Ground-Penetrating Radar
GRS/NS	Gamma Ray Spectrometer/Neutron Spectrometer
HEOMD	(NASA) Human Exploration and Operations Directorate
HiRISE	High Resolution Imaging Science Experiment (instrument on MRO)
HRSC	High Resolution Stereo Camera (instrument on MEx)
ICE-SAG	Ice and Climate Evolution Science Analysis Group
InSAR	Interferometric Synthetic Aperture Radar
InSight	Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (NASA mission)
ISRU	In Situ Resource Utilization
JPL	Jet Propulsion Laboratory
LIBS	Laser Induced Breakdown Spectroscopy
LiDAR	Light Detection and Ranging
LPSC	Lunar and Planetary Science Conference
MARCI	Mars Color Imager
MARSIS	Mars Advanced Radar for Subsurface and Ionosphere Sounding
MAVEN	Mars Atmosphere and Volatile Evolution (NASA mission)
MCS	Mars Climate Sounder (instrument on MRO)
MEDA	Mars Environmental Dynamics Analyzer (instrument on 2020 Mars rover mission)
MEP	Mars Exploration Program
MEPAG	Mars Exploration Program Analysis Group
MER	Mars Exploration Rovers (NASA missions)

MET	Meteorology
MEx	Mars Express (ESA mission)
MGS	Mars Global Surveyor (NASA mission)
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MOC	Mars Orbiter Camera (instrument on MGS)
MOLA	Mars Orbiter Laser Altimeter (instrument on MGS)
MONS/GRS	Mars Odyssey Neutron Spectrometer/Gamma Ray Spectrometer (instrument on ODY)
MPO	Mars Program Office
MRO	Mars Reconnaissance Orbiter (NASA mission)
MSL	Mars Science Laboratory (NASA mission)
NASA	National Aeronautics and Space Administration
NEX-SAG	NEXt (Mars Orbiter) Science Analysis Group
NF	New Frontiers
NPLD	North Polar Layered Deposits
NPRC	North Polar Residual Cap
ODY	Mars Odyssey (NASA mission)
OPP	(NASA) Office of Planetary Protection
OMEGA	Visible and Infrared Mineralogical Mapping Spectrometer (instrument on MEx)
PLD	Polar Layered Deposits
PSAR	Polarimetric Synthetic Aperature Radar
PSI	Planetary Science Institute
RAT	Rock Abrasion Tool
REMS	Rover Environmental Monitoring Station (instrument on MSL)
RH	Relative Humidity
RHU	Radioisotope Heater Unit
RSL	Recurring Slope Lineae
RTG	Radioisotope Thermoelectric Generator
SAG	Science Analysis Group
SAM	Sample Analysis at Mars
SAR	Synthetic Aperture Radar
SEP	Solar-Electric Propulsion
SETI	Search for Extraterrestrial Intelligence
SHARAD	Shallow Radar Sounder (instrument on MRO)
SHIELD	Small, High Impact Energy Landing Device
SMD	NASA Science Mission Directorate
SMOW	Standard Mean Ocean Water
SPLD	South Polar Layered Deposits
SPRC	South Polar Residual Cap
SS	Small Spacecraft
SWIR	Short Wave Infrared
TECP	Thermal Electrical Conductivity Probe
TEM	Transient Electro-Magnetic

TES	Thermal Emission Spectrometer
TGO	Trace Gas Orbiter (ESA mission)
THEMIS	Thermal Emission Imaging System (instrument on ODY)
TIR	Thermal Infrared
T-LS	Tunable Laser Spectrometer (generic instrument type)
TKS	Tunable Laser Spectrometer (instrument on MSL)
VM	Virtual Meeting
XCT	X-Ray Computed Tomography

Appendix F: References

Abshire, J.B., Guzewich, S.D. Smith, M.D., Riris, H., Sun, X., Gentry, B.M., Yu, A., Allan, G.R., 2018. MARLI: MARs LIdar for global wind and aerosol profiles from orbit. *at* International Workshop on Instrumentation for Planetary Missions, Ab. 4034.

Aharonson, O., Zuber, M.T., Rothman, D.H., 2001. Statistics of Mars' topography from the Mars orbiter laser altimeter: slopes, correlations and physical models. *J. Geophys. Res.* **106** (E10), 23723–23735. doi:10.1029/2000JE001403.

Aharonson, O., Zuber, M.T., et al., 2004. Depth, distribution, and density of CO_2 deposition on Mars. *J. Geophys. Res.* **109**, E05004. doi:10.1029/2003JE002223.

Appéré, T., Schmitt, B., et al., 2011. Winter and spring evolution of northern seasonal deposits on Mars from OMEGA on Mars express. *J. Geophys. Res.* **116**, E05001. doi:10.1029/2010JE003762.

Arthern, R.J., Winebrenner, D.P., Waddington, E.D., 2000. Densification of water ice deposits on the residual north polar cap of Mars. *Icarus* **144**, 367–381. doi:10.1006/icar.1999.6308.

Baker, M.M., et al., 2018. The Bagnold Dunes in southern summer: Active sediment transport on Mars observed by the Curiosity rover. *Geophys. Res. Lett.* **45**(17), 8853–8863. doi:10.1029/2018GL079040.

Bandfield, J.L., 2007. High-resolution subsurface water-ice distributions on Mars. *Nature* **447**, 64–67. doi:10.1038/nature05781.

Banfield, D., Spiga, A., et al., 2019. First atmospheric results from InSight APSS. *at* 50th Lunar and Planetary Science Conference, Ab. 2699.

Bapst, J., Bandfield, J.L., Wood, S.E., 2015. Hemispheric asymmetry in martian seasonal surface water ice from MGS TES. *Icarus* **260**, 396–408. doi:10.1016/j.icarus.2015.07.025.

Barnes, J.R., Haberle, R.M., et al., 2017. The global circulation, in: Haberle, R.M., Clancy, R.T., Forget, F., Smith, M.D., Zurek, R.W. (Eds.), *The atmosphere and climate of Mars.* Cambridge University Press. 229–294. doi:10.1017/9781139060172.009.

Becerra, P., Byrne, S., Sori, M.M., Sutton, S., Herkenhoff, K.E., 2016. Stratigraphy of the north polar layered deposits of Mars from high-resolution topography. *J. Geophys. Res. Planets* **121**, 1445–1471. doi:10.1002/2015JE004992.

Becerra, P., Sori, M.M., Byrne, S., 2017. Signals of astronomical climate forcing in the exposure topography of the north polar layered deposits of Mars. *Geophys. Res. Lett.* **44**, 62–70. doi: 10.1002/2016GL071197.

Beck, P., Pommerol, A., Schmitt, B., Brissaud, O., 2010. Kinetics of water adsorption on minerals and the breathing of the Martian regolith. *J. Geophys. Res.* **115**, E10011. doi:10.1029/2009JE003539.

Beer, J., Raisbeck, G.M., Yiou, F., 1991. Time variations of Be-10 and solar activity. *in* The sun in time, 343–359.

Benson, J.L., James, P.B., 2005. Yearly comparisons of the martian polar caps: 1999-2003 Mars Orbiter Camera observations. *Icarus* **174**, 513–523. doi:10.1016/j.icarus.2004.08.025.

Bierson, C.J., Phillips, R.J., et al., 2016. Stratigraphy and evolution of the buried CO_2 deposit in the Martian south polar cap. *Geophys. Res. Lett.* **43**, 4172–4179. doi:10.1002/2016GL068457.

Bish, D. L., Blake, D. F., et al., 2013. X-ray diffraction results from Mars Science Laboratory: mineralogy of Rocknest at Gale Crater. *Science* **341**(6153), 1238932. doi:10.1126/science.1238932.

Bishop, J.L., Pieters, C.M., Edwards, J.O., 1994. Infrared spectroscopic analyses on the nature of water in montmorillonite. *Clay and Clay Minerals* **42**(6), 702–716.

Bonev, B.P., Hansen, G.B., et al., 2008. Albedo models for the residual south polar cap on Mars: Implications for the stability of the cap under near-perihelion global dust storm conditions. *Planet. Space Sci.* **56**. 181–193. doi:10.1016/j.pss.2007.08.003.

Bonev, B.P., James, P.B., Bjorkman, J.E., Wolff, M.J., 2017. Regression of the mountains of Mitchel polar ice after the onset of a global dust storm on Mars. *Geophys. Res. Lett.* **29** (21). doi:10.1029/2002GL015458.

Box, J. E., Fettweis, X., Stroeve, J.C., Tedesco, M., Hall, D.K., Steffen, K., 2012. Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers. *The Cryosphere* **6**, 821-839. doi:10.5194/tc-6-821-2012.

Boynton, W.V., Feldman, W.C., et al., 2002. Distribution of Hydrogen in the Near Surface of Mars: Evidence for Subsurface Ice Deposits. *Science* **297**(5578), 81–85. doi:10.1126/science.1073722.

Bramson, A. M., Byrne, S., et al., 2015. Widespread excess ice in Arcadia Planitia, Mars. *Geophys. Res. Lett.* **42**, 6566-6574. doi:10.1002/2015GL064844.

Bramson, A. M., Byrne, S., Bapst, J., 2017. Preservation of midlatitude ice sheets on Mars. *J. Geophys. Res.* **122**, 22250–2266. doi:10.1002/2017JE005357.

Bridges, N. T., Geissler, P., Silvestro, S., Banks, M., 2013. Bedform migration on Mars: current results and future plans. *Aeolian Res.* **9**, 133–151. doi:10.1016/j.aeolia.2013.02.004.

Bridges, N.T., Sullivan, et al., 2017. Martian aeolian activity at the Bagnold Dunes, Gale Crater: the view from the surface and orbit. *J. Geophys. Res. Planets* **122**, 2077–2110. doi:10.1002/2017JE005263.

Brophy, J., 2011. The Dawn Ion Propulsion System. In: Russell C., Raymond C. (eds) *The Dawn Mission to Minor Planets 4 Vesta and 1 Ceres*. Springer, New York, NY, pp 251-261.

Brothers, T.C., Holt, J.W., Spiga, A., 2015. Planum Boreum basal unit topography, Mars: irregularities and insights from SHARAD. *J. Geophys. Res. Planets* **120**, 1357–1375. doi:10.1002/2015JE004830.

Brothers, S.C., Kocurek, G., Holt, J.W., 2018. Sequence architecture of the cavi unit, Chasma Boreale, Mars. *Icarus* **308**, 42–60. doi:10.1016/j.icarus.2017.06.024.

Brown, A.J., Calvin, W.M., Murchie, S.L., 2012. Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) north polar springtime recession mapping: first 3 Mars years of observations. *J. Geophys. Res.* **117**, E00J20. doi:10.1029/2012JE004113.

Brown, A. J., Piqueux, S., Titus, T.N., 2014. Interannual observations and quantification of summertime H_2O ice deposition on the Martian CO_2 ice south polar cap. *Earth Planet. Sci. Lett.* **406**, 102–109. doi:10.1016/j.epsl.2014.08.039.

Brown, A.J., Calvin, W.M., Becerra, P., Byrne, S., 2016. Martian north polar cap summer water cycle. *Icarus* **277**, 401–415. doi:10.1016/j.icarus.2016.05.007.

Bryson, K.L., Chevrier, V., Sears, D.W.G., Ulrich, R., 2008. Stability of ice on Mars and the water vapor diurnal cycle: experimental study of the sublimation of ice through a fine-grained basaltic regolith. *Icarus* **196**(2), 446–458. doi:10.1016/j.icarus.2008.02.011.

Burr, D. M., Tanaka, K. L., Yoshikawa, K., 2009. Pingos on Earth and Mars. *Planet. Space Sci.* **57**, 541–555, doi:10.1016/j.pss.2008.11.003.

Byrne, S., Murray, B.C., 2002. North polar stratigraphy and the paleo-erg of Mars. *J. Geophys. Res. Planets* **107**(E6), 11-1–11-12. doi:10.1029/2001JE001615.

Byrne, S., Dundas, C.M., et al., 2009. Distribution of Mid-Latitude Ground Ice on Mars from New Impact Craters. *Science* **325**(5948), 1674–1676. doi:10.1126/science.1175307.

Calvin, W.M., Roach, et al., 2009. Compact Reconnaissance Imaging Spectrometer for Mars observations of northern Martian latitudes in summer. *J. Geophys. Res.* **114**, E00D11. doi:10.1029/2009JE003348.

Calvin, W.M., James, P.B., Cantor, B.A., Dixon, E.M., 2015. Interannual and seasonal changes in the north polar ice deposits of Mars: observations from MY 29-31 using MARCI. *Icarus* **251**, 181–190. doi:10.1016/j.icarus.2014.08.026.

Calvin, W. M., Cantor, B.C., James, P. B., 2018. Mars north polar cap recession and summer variation: five Mars years of MARCI observations. *at* 49th Lunar and Planetary Science Conference, Ab. 2455.

Campbell, B. A., Morgan, G. A., 2018. Fine-scale layering of Mars polar deposits and signatures of ice content in nonpolar material from multiband SHARAD data processing. *Geophys. Res. Lett.* **45**, 1759–1766. doi:10.1002/2017GL075844.

Carr, M.H., 1996. *Water on Mars.* Oxford University Press. 248pp.

Carter, L.M., Campbell, et al., 2009. Shallow radar (SHARAD) sounding observations of the Medusae Fossae Formation, Mars. *Icarus* **199**(2), 295–302. doi:10.1016/j.icarus.2008.10.007.

Chamberlain, M.A., Boynton, W.V., 2007. Response of Martian ground ice to orbit-induced climate change. *J. Geophys. Res.* **112**, E06009, doi:10.1029/2006JE002801.

Chevrier, V. F., Hanley, J.,Altheide, T. S., 2009. Stability of perchlorate hydrates and their liquid solutions at the Phoenix landing site, Mars. *Geophys. Res. Lett.* **36**, L10202. doi:10.1029/2009GL037497.

Christner, B.C., Mosley-Thompson, E., Thompson, L.G., Reeve, J.N., 2003. Bacterial recovery from ancient ice. *Environ. Microbiol.* **5**, 433–436. doi:10.1046/j.1462-2920.2003.00422.x.

Christner, B.C., Priscu, J.C., Achberger, A.M., Barbante, C., Carter, S.P., et al., 2014. A microbial ecosystem beneath the West Antarctic ice sheet. *Nature* **512**, 310–313. doi:10.1038/nature13667.

Clancy, R.T., Grossman, A.W., et al., 1996. Water vapor saturation at low altitudes around Mars aphelion: a key to Mars climate? *Icarus* **122**, 36–62. doi:10.1006/icar.1996.0108.

Clancy, R.T., Montmessin, F., Benson, J., Daerden, F., Colaprete, A., Wolff, M.J., 2017. 5. Mars Clouds, in *The Atmosphere and Climate of Mars*, edited by R. M. Haberle, R. T. Clancy, F. Forget, M. D. Smith, and R. W. Zurek, pp. 76–105, Cambridge University Press, Cambridge, United Kingdom.

Colaprete, A., Barnes, J.R., Haberle, R.M., Montmessin, F., 2008. CO_2 clouds, CAPE and convection on Mars: Observations and general circulation modeling. *Planet. Space Sci.* **56**(2), 150–180. doi:10.1006/icar.1996.0108.

Conway, S.J., de Haas, T., Harrison, T.N., 2018. Martian gullies: a comprehensive review of observations, mechanisms and insights from Earth analogues. *Geo. Soc. London, Special Publications* **467,** 7–66. doi:10.1144/SP467.14.

Costard, F.M., Kargel, J.S., 1995. Outwash plains and thermokarst on Mars. *Icarus* **114**(1), 93–112. doi:10.1006/icar.1995.1046.

CReSIS. 2016. CReSIS Radar Depth Sounder Data, Lawrence, Kansas, USA. Digital Media. http://data.cresis.ku.edu/.

Criss, R.E., 1999. Principles of Stable Isotope Distribution. Oxfort University Press. 264pp.

Dash, J.G., Rempel, A.W., Wettlaufer, J.S., 2006. The physics of premelted ice and its geophysical consequences. *Rev. Mod. Phys.* **78**, 695–741. doi:10.1103/RevModPhys.78.695.

Dauber, I.J., McEwen, A.S., Byrne, S., Kennedy, M.R., Ivanov, B., 2013. The current martian cratering rate. *Icarus* **225**, 506–516. doi:10.1016/j.icarus.2013.04.009.

Davy, R., Davis, J.A., Taylor, P.A., Lange, C.F., Weng, W., Whiteway, J., Gunnlaugson, H.P. 2010. Initial analysis of air temperature and related data from the Phoenix MET station and their use in estimating turbulent heat fluxes. *J. Geophys. Res.* **115**, E00E13. doi:10.1029/2009JE003444.

de Vera, J.-P., Alawi, M., Backhaus, T., Baque, M., Billi, et al., 2019. Limits of life and the habitability of Mars: the ESA space experiment BIOMEX on the ISS. *Astrobiology* **19**(2), 145–157. doi:10.1089/ast.2018.189.

D'Elia, T., Veerapaneni, R, Rogers, S.O., 2008. Isolation of microbes from Lake Vostok accretion ice. *Appl. Environ. Microbiol.* **74**(15), 4962–4965. doi:10.1128/AEM.02501-07.

Diniega, S., Smith, I.B., *submitted. H*igh-priority Science Questions identified at the Mars Workshop on Amazonian and Present-Day Climate. *Planet. Space Sci.*

Diniega, S., Byrne, S., Bridges, N., Dundas, C.M., McEwen, A.S., 2010. Seasonality of present-day Martian dune-gully activity. *Geology* **38**(11), 1047–1050, doi:10.1130/G31287.1.

Diniega, S., Hansen, C.J., et al., 2013. A new dry hypothesis for the formation of martian linear gullies. *Icarus* **225**, 526–537. doi:10.1016/j.icarus.2013.04.006.

Diniega, S., Hansen, C.J., Allen, A., Grigsby, N., Li, Z., Perez, T., Chojnacki, M., 2017. Dune-slope activity due to frost and wind throughout the north polar erg, Mars. *Geo. Soc. London, Special Publications* **467**, SP467.6. doi:10.1144/SP467.6.

Dragosics M., Meinander, O., et al., 2016. Insulation effects of Icelandic dust and volcanic ash on snow and ice. *Arab. J. Geosci.* **9**, 126. doi: 10.1007/s12517-015-2224-6.

Dundas, C.M., Byrne, S., 2010. Modeling sublimation of ice exposed by new impacts in the Martian mid-latitudes. *Icarus* **206**, 716–728. doi:10.1016/j.icarus.2009.09.007.

Dundas, C. M., Byrne, S., McEwen, et al., 2014. HiRISE observations of new impact craters exposing Martian ground ice. *J. Geophys. Res. Planets* **119**, 109–127. doi:10.1002/2013JE004482.

Dundas, C. M., Byrne, S., McEwen, A.S., 2015. Modeling the development of martian sublimation thermokarst landforms. *Icarus* **262**, 154–169. doi:10.1016/j.icarus.2015.07.033.

Dundas, C.M., McEwen, A.S., Diniega, S., Hansen, C.J., Byrne, S., McElwaine, J.N., 2017a. The formation of gullies on Mars today. *Geo. Soc. London, Special Publications* **467**, 467.7. doi:10.1144/SP467.5.

Dundas, C.M., McEwen, A.S., Chojnacki, M., et al., 2017b. Granular flows at recurring slope lineae on Mars indicate a limited role for liquid water. *Nature Geosci.* **10**, 903–907. doi:10.1038/s41561-017-0012-5.

Dundas, C. M., Bramson, A.M., et al., 2018. Exposed subsurface ice sheets in the Martian mid-latitudes. *Science* **359**(6372), 199–201. doi:10.1126/science.aao1619.

Durham, W.B., Kirby, S.H., Stern, L.A., 1999. Steady-state flow of solid CO_2: preliminary results. *Geophys. Res. Lett.* **26**, 3493–3496. doi:10.1029/1999GL008373.

Durham, W.B., Prieto-Ballesteros, O., Goldsby, D.L., Kargel, J.S., 2010. Rheological and thermal properties of icy materials. *Space Science Reviews* **153**, 273–298. doi:10.1007/s11214-009-9619-1.

Edwards, C. S., Piqueux, S., 2016. The water content of recurring slope lineae on Mars. *Geophys. Res. Lett.* **43**, 8912–8919. doi:10.1002/2016GL070179.

Eigenbrode, J.L., Glass, B., McKay, C.P., Niles, P., Spry, J.A., 2019. Martian subsurface ice science investigation. *at* Mars extant life: What's next? Conference.

Eluszkiewicz, J., 1993. On the microphysical state of the Martian seasonal caps. *Icarus* **103**(1), 43–48. doi:10.1006/icar.1993.1056.

Etiope, G., Oehler, D.Z., 2019. Methane spikes, background seasonality and non-detections on Mars: a geological perspective. *Planet. Space Sci.* **168**, 52–61. doi:10.1016/j.pss.2019.02.001.

Fanale, F.P., Salvail, J.R., Zent, A.P., Postawko, S.E., 1986. Global distribution and migration of subsurface ice on Mars. *Icarus* **67**(1), 1–18. doi:10.1016/0019-1035(86)90170-3.

Farley, K.A., Malespin, C., et al., 2014. In situ radiometric and exposure age dating of the martian surface. *Science* **343**(6169), 1247166. doi:10.1126/science.1247166.

Farmer,C.B., Doms, P.E., 1979. Global seasonal variation of water vapor on Mars the implications of permafrost. *J. Geophys. Res*. **84**(B6), 2881–2888. doi:10.1029/JB084iB06p02881.

Farris, H.N., Conner, M.B., Chevrier, V.F., Rivera-Valentin, E.G., 2018. Adsorption driven regolith-atmospheric water vapor transfer on Mars: An analysis of Phoenix TECP data. *Icarus* **308**, 71–75. doi:10.1016/j.icarus.2017.08.002.

Feldman, W.C., Mellon, M.T., et al., 2008. Volatiles on Mars: scientific results from the Mars Odyssey Neutron Spectrometer, in: Bell, J.F. (Ed.), *The Martian Surface: Composition, Mineralogy, and Physical Properties.* Cambridge University Press, London, 125–148. doi:10.1017/CBO9780511536076.007.

Feldman, W. C., Pathare, A., et al., 2011. Mars Odyssey neutron data: 2. Search for buried excess water ice deposits at nonpolar latitudes on Mars. *J. Geophys. Res.* **116**, E11009. doi:10.1029/2011JE003806.

Fenton, L.K., Richardson, M.I., 2001. Martian surface winds: Insensitivity to orbital changes and implications for aeolian processes. *J. Geophys. Res.* **106**(E12), 32885–32902. doi:10.1029/2000JE001407.

Fischer, E., Martínez, G., Elliot, H.M., Rennó, N.O., 2014. Experimental evidence for the formation of liquid saline water on Mars. *Geophys. Res. Lett.* **41**, 4456–4462. doi:10.1002/2014GL060302.

Fishbaugh, K.E., Head, J.W., 2005. Origin and characteristics of the Mars north polar basal unit and implications for polar geologic history. *Icarus* **174**(2), 444–474. doi:10.1016/j.icarus.2004.06.021.

Fishbaugh, K. E., Hvidberg, C.S., 2006. Martian north polar layered deposits stratigraphy: Implications for accumulation rates and flow. *J. Geophys. Res.* **111**, E06012. doi:10.1029/2005JE002571.

Fishbaugh, K.E., Hvidberg, C.S., Byrne, S., et al., 2010. First high-resolution stratigraphic column of the Martian north polar layered deposits. *Geophys. Res. Lett.* **37**, L07201. doi:10.1029/2009GL041642.

Fjeldbo, G., Sweetnam, D., Brenkle, J., Christensen, E., Farless, D., Mehta, J., Seidel, B., Michael Jr, W., Wallio, A. and Grossi, M., 1977. Viking radio occultation measurements of the Martian atmosphere and topography: Primary mission coverage. *J. Geophys. Res.* **82**(28), 4317–4324.

Forget, F., Haberle, R.M., Montmessin, F., Levrard, B., Head, J., 2006. Formation of glaciers on Mars by atmospheric precipitation at high obliquity. *Science* **311**, 368–371. doi:10.1126/science.1120335.

Forget, F., Byrne, S., Head, J.W., Mischna, M.A., Schörghofer, N., 2017. Recent climate variations, in: Haberle, R.M., Clancy, R.T., Forget, F., Smith, M.D., Zurek, R.W. (Eds.), *The atmosphere and climate of Mars.* Cambridge University Press. 497–525. doi:10.1017/9781139060172.016.

Formisano, V., Atreya, S., Encrenaz, T., Ignatiev, N., Giuranna, M., 2004. Detection of methane in the atmosphere of Mars. *Science* **306**, 1758–1761.

Fu, X., Wang, A., Krawczynski, M.J., 2017. Characterizing amorphous silicates in extraterrestrial materials: Polymerization effects on Raman and mid-IR spectral features of alkali and alkali earth silicate glasses. *J. Geophys. Res. Planets* **122**, 839–855. doi:10.1002/2016JE005241.

Gabriel, T.S.J., Hardgrove, C., Czarnecki, S., Rampe, E.B., Rapin, W., Achilles, C.N., Sullivan, D., Nowicki, S., Thompson, L., Litvak, M., Mitrofanov, I., 2018. Water abundance of dunes in Gale crater, Mars from active neutron experiments and implications for amorphous phases. *Geophys. Res. Lett.* **45**(23), 12,766–12,775. doi:10.1029/2018GL079045.

Gallagher, C., Balme, M.R., 2011. Landforms indicative of ground-ice thaw in the northern high latitudes of Mars. *Geo. Soc. London, Special Publications* **356**(1), 87–110. doi:10.1144/SP356.6.

Gallagher, C., Balme, M.R., Conway, S.J., Grindrod, P.M., 2011. Sorted clastic stripes, lobes and associated gullies in high-latitude craters on Mars: Landforms indicative of very recent, polycyclic ground-ice thaw and liquid flows. *Icarus* **211**, 458–471, doi:10.1016/j.icarus.2010.09.010.

Gehler, A., Gingerich, P.D., Pack, A., 2016. Temperature and atmospheric CO_2 concentration estimates through the PETM using triple oxygen isotope analysis of mammalian bioapatite. *Proc. Natl. Acad. Sci.* **113**(28), 7739–7744. doi:10.1073/pnas.1518116113.

Geissler, P.E., Fenton, L.K., Enga, M.-T., Mukherjee, P., 2016. Orbital monitoring of Martian surface changes. *Icarus* **278**, 279–300. doi:10.1016/j.icarus.2016.05.023.

Geminale, A., Formisano, V., Sindoni, G., 2011. Mapping methane in Martian atmosphere with PFS-MEX data. *Planet. Space Sci.* **59**, 137–148. doi:10.1016/j.pss.2010.07.011.

Genova, A., Goossens, S., et al., 2016. Seasonal and static gravity field of Mars from MGS, Mars Odyssey and MRO radio science. *Icarus* **272**, 228–245. doi:10.1016/j.icarus.2016.02.050.

Giuranna, M., Viscardy, S., et al., 2019. Independent confirmation of a methane spike on Mars and a source region east of Gale crater. *Nat. Geosci.* doi:10.1038/s41561-019-0331-9.

Gómez-Elvira, J., Armiens, C., et al., 2012. REMS: The environmental sensor suite for the Mars Science Laboratory Rover, *Space Sci. Rev.* **170**, 583–640. doi:10.1007/s11214-012-9921-1.

Gómez-Elvira, J., et al., 2014. Curiosity's rover environmental monitoring station: Overview of the first 100 sols. *J. Geophys. Res. Planets* **119**, 1680–1688. doi:10.1002/2013JE004576.

Gooding, J.L., 1986. Martian dust particles as condensation nuclei: A preliminary assessment of mineralogical factors. *Icarus* **66**, 56–74. doi:10.1016/0019-1035(86)90006-0.

Gough, R.V., Chevrier, V.F., Baustian, K.J., Wise, M.E., Tolbert, M.A., 2011. Laboratory studies of perchlorate phase transitions: Support for metastable aqueous perchlorate solutions on Mars. *Earth Planet. Sci. Lett.* **312**(3–4), 371–377. doi:10.1016/j.epsl.2011.10.026.

Gough, R.V., Chevrier, V.F., Tolbert, M.A., 2014. Formation of aqueous solutions on Mars via deliquescence of chloride–perchlorate binary mixtures. *Earth Planet. Sci. Lett.* **393**, 73–82. doi:10.1016/j.epsl.2014.02.002.

Gough, R.V., Chevrier, V.F.,Tolbert, M.A., 2016. Formation of liquid water at low temperatures via the deliquescence of calcium chloride: Implications for Antarctica and Mars. *Planet. Space Sci.* **131**, 79–87. doi:10.1016/j.pss.2016.07.006.

Greenwood, J.P., Itoh, S., Sakamoto, N., Vicenzi, E.P., Yurimoto, H., 2008. Hydrogen isotope evidence for loss of water from Mars through time. *Geophys. Res. Lett.* **35**, L05203. doi:10.1029/2007GL032721.

Greybush, S.J., Wilson, R.J., Hoffman, R.N., et al., 2012. Ensemble Kalman filter data assimilation of Thermal Emission Spectrometer temperature retrievals into a Mars GCM. *J. Geophys. Res.* **117**(E11), E11008. doi:10.1029/ 2012JE004097.

Grima, C., Kofman, W., et al., 2009. North polar deposits of Mars: Extreme purity of the water ice. *Geophys. Res. Lett.* **36**, L03203. doi:10.1029/2008GL036326.

Grimm, R. E., Stillman, D. E., 2015. Field test of detection and characterisation of subsurface ice using broadband spectral-induced polarisation. *Permafrost and Periglacial Processes* **26**(1), 28–38. doi:10.1002/ppp.1833.

Grimm, R., Stillman, et al., 2018. Mars DartDrop: Assessing contemporary habitability at recurring slope lineae with a simple in situ mission. *at* 49th Lunar and Planetary Science Conference, Ab. 1097.

Haberle, R.M., Murphy, J.R. and Schaeffer, J., 2003. Orbital change experiments with a Mars general circulation model. *Icarus* **161**(1), 66–89. doi:10.1016/S0019-1035(02)00017-9.

Haberle, R. M., Forget, F., et al., 2008. The effect of ground ice on the Martian seasonal CO_2 cycle. *Planet. Space Sci.* **56(**2), 251–255. doi:10.1016/j.pss.2007.08.006.

Haberle, R.M., Gomez-Elvira, J., et al., 2014. Preliminary interpretation of the REMS pressure data from the first 100 sols of the MSL mission. *J. Geophys. Res.* **119**(3), 440–453. doi:10.1002/2013JE004488.

Hanna, R. D., Ketcham, R.A., 2017. X-ray computed tomography of planetary materials: A primer and review of recent studies. *Chemie Der Erde - Geochemistry,* **77**(4), 547–572. doi:10.1016/j.chemer.2017.01.006.

Hansen, C.J., Diniega, S., et al., 2015. Agents of change on Mars' northern dunes: CO_2 ice and wind. *Icarus* **251**, 264–274. doi:10.1016/j.icarus.2014.11.015.

Hansen, C.J., Diniega, S., Hayne, P.O., 2018. Mars' snowfall and sand avalanches. *at* 49th Lunar and Planetary Science Conference, Ab. 2175.

Hansen, G.B., 1997. The infrared absorption spectrum of carbon dioxide ice from 1.8 to 333 µm. *J. Geophys. Res.* **102**(E9), 21569–21587. doi:10.1029/97JE01875.

Harri, A.-M., Genzer, M., et al., 2014. Mars Science Laboratory relative humidity observations: Initial results. *J. Geophys. Res. Planets* **119**, 2132–2147. doi:10.1002/2013JE004514.

Hauber, E., van Gasselt, S., Chapman, M. G., and Neukum, G., 2008. Geomorphic evidence for former lobate debris aprons at low latitudes on Mars: Indicators of the Martian paleoclimate. *J. Geophys. Res.* **113**, E02007, doi:10.1029/2007JE002897.

Hayne, P.O., Paige, D.A., Heavens, N.G., 2014. The role of snowfall in forming the seasonal ice caps of Mars: Models and constraints from the Mars Climate Sounder. *Icarus* **231**, 122–130. doi:10.1016/j.icarus.2013.10.020.

Hayne, P. O., Byrne, S., Smith, I. B., Banfield, D., Staehle, R. L., 2018. Mars PolarDROP: Distributed Micro-landers to investigate the polar ice caps and climate of Mars. *at* Mars Exploration Program Analysis Group, Meeting 36, Crystal City, Virginia, Forum Ab. 12.

Head, J. W, Mustard, J.F., Kreslavsky, M.A., Milliken, R.E., Marchant, D.R., 2003. Recent ice ages on Mars. *Nature* **426**, 797–802. doi:10.1038/nature02114.

Head, J. W., Neukum, G., et al., 2005. Tropical to mid-latitude snow and ice accumulation, flow, and glaciation on Mars. *Nature* **434**, 346–351, doi:10.1038/nature03359.

Heavens, N.G., Johnson, M.S., Abdou, W.A., Kass, D.M., Kleinböhl, A., McCleese, D.J., Shirley, J.H., Wilson, R.J., 2014. Seasonal and diurnal variability of detached dust layers in the tropical martian atmosphere, *J. Geophys. Res.* **119**, 1748-1774. doi:10.1002/2014JE004619.

Hecht, M. H., 2002. Metastability of liquid water on Mars. *Icarus* **156**(2), 373-386. doi:10.1006/icar.2001.6794.

Hecht, M., Carsey, F., 2005. Subsurface Ice Probe. *NASA Tech Briefs.* www.techbriefs.com/component/content/article/tb/techbriefs/physical-sciences/169.

Hecht, M.H., the Chronos Team, 2006. CHRONOS: A journey through martian history. *at* Fourth International Mars Polar Science Conference, Ab. 8096.

Herkenhoff, K.E.,Soderblom, L.A., Kirk, R.L., 2002. MOC Photoclinometry of the north polar residual cap on Mars. *at* 33rd Lunar and Planetary Science Conference, Ab. 1714.

Herkenhoff, K.E., Byrne, S., Russell, P.S, Fishbaugh, K.E., McEwen, A.S., 2007. *Science* **21**, 1711–1715. doi:10.1126/science.1143544.

Hess, S.L., Henry, R.M., Leovy, C.B., Ryan, J.A., Tillman, J.E., 1977. Meteorological results from the surface of Mars: Viking 1 and 2. *J. Geophys. Res.* **82**(28), 4559–4574. doi:10.1029/JS082i028p04559.

Hinnov, L.A., 2013. Cyclostratigraphy and its revolutionizing applications in the earth and planetary sciences. *Geol. Soc. Am. Bull.* **125**(11-12), 1703–1734; doi:10.1130/B30934.1.

Hinson, D.P., Simpson, R.A., Twicken, J.D., Tyler, G.L. and Flasar, F.M., 1999. Initial results from radio occultation measurements with Mars Global Surveyor. *J. Geophys. Res. Planets* **104**(E11), 26997–27012.

Hollingsworth, J.L., Haberle, R.M., Barnes, J.R., Bridger, A.F., Pollack, J.B., Lee, H., Schaeffer, J., 1996. Orographic control of storm zones on Mars. *Nature* **380**(6573), 413–416.

Holmes, J.A., Lewis, S.R., Patel, M.R., 2015. Analysing the consistency of martian methane observations by investigation of global methane transport. *Icarus* **257**, 23–32.

Holstein-Rathlou, C., Thomas, P.E., Merrison, J., Iversen, J.J., 2018. Wind turbine power production under current Martian atmospheric conditions. *at* Mars Workshop on Amazonian and Present-Day Climate, Ab. 4004.

Holt, J.W., Safaeinili, et al., 2008. Radar sounding evidence for buried glaciers in the southern mid-latitudes of Mars. *Science* **322**(5905), 1235–1238. doi:10.1126/science.1164246.

Hörhold, M.W., Laepple, T., et al., 2012. On the impact of impurities on the densification of polar firn. *Earth Planet. Sci. Lett.* **325–326**, 93–99. doi: 10.1016/j.epsl.2011.12.022.

Hudson, T.L., Aharonson, O., Schorghofer, N., et al., 2007. Water vapor diffusion in Mars subsurface environments. *J. Geophys. Res.* **112**, E05016. doi:10.1029/2006JE002815.

Hudson, T.L., Aharonson, O., 2008. Diffusion barriers at Mars surface conditions: Salt crusts, particle size mixtures, and dust. *J. Geophys. Res.* **113**, E09008. doi:10.1029/2007JE003026.

Hvidberg, C.S., Fishbaugh, K.E., et al., 2012. Reading the climate record of the Martian polar layered deposits. *Icarus* **221**, 405–419. doi:10.1016/j.icarus.2012.08.009

Ingersoll, A.P., 1970. Mars: Occurrence of liquid water. *Science* **168**, 972–973. doi:10.1126/science.168.3934.972.

Ivanov, A.B., Muhleman, D.O., 2001. Cloud reflection observations: results from the Mars Orbiter Laser Altimeter. *Icarus* **154**, 190–206. doi:10.1006/icar.2001.6686.

Jaeger, W.L., Keszthelyi, L.P., McEwen, A.S., Dundas, C.M., Russell, P.S., 2007. Athabasca Valles, Mars: A lava-draped channel system. *Science* **317**, 1709–1711. doi:10.1126/science.1143315.

Jakosky, B.M., 1983. The role of seasonal reservoirs in the Mars water cycle: I. Seasonal exchange of water with the regolith. *Icarus* **55**, 1–18. doi:10.1016/0019-1035(83)90046-5.

Jakosky, B.M, Barker, E.S., 1984. Comparison of ground-based and Viking Orbiter measurements of Martian water vapor: Variability of the seasonal cycle. *Icarus* **57**(3), 322–334. doi:10.1016/0019-1035(84)90121-0.

Jakosky, B.M., Carr, M.H., 1985. Possible precipitation of ice at low latitudes of Mars during periods of high obliquity. *Nature* **315**, 559–561. doi:10.1038/315559a0.

Jakosky, B.M., Farmer, C.B., 1982. The seasonal and global behavior of water-vapor in the Mars atmosphere -complete global results of the Viking Atmospheric Water Detector experiment. *J. Geophys. Res.* **87**, 2999-3019.

Jakosky, B.M., Zent, A.P., Zurek, R.W., 1997. The Mars water cycle: Determining the role of exchange with the regolith. *Icarus* **130**, 87–95, doi:10.1006/icar.1997.5799.

Jakosky, B.M., Nealson, K.H., Bakermans, C., Ley, R.E., Mellon, M.T., 2004. Subfreezing activity of microorganisms and the potential habitability of Mars' polar regions. Astrobiology 3 (2), 343–350. doi:10.1089/153110703769016433.

Jakosky, B.M., Brain, D., et al., 2018. Loss of the Martian atmosphere to space: Present-day loss rates determined from MAVEN observations and integrated loss through time. *Icarus* **315**, 146–157. doi:10.1016/j.icarus.2018.05.030.

Jänchen, J., Bish, D.L., Möhlmann, D.T.F., Stach, H., 2006. Investigation of the water sorption properties of Mars-relevant micro- and mesoporous minerals. *Icarus* **180**, 353–358. doi:10.1016/j.icarus.2005.10.010.

Jänchen, J., Morris, R.V., Bish, D.L., Janssen, M., Hellwig, U., 2009. The H_2O and CO_2 adsorption properties of phyllosilicate-poor palagonitic dust and smectites under Martian environmental conditions. *Icarus* **200**, 463–467. doi:10.1016/j.icarus.2008.12.006.

Johnson, J.E., Spry, J.A., Race, M.S., Conley, C.A., Siegel, B., 2016. NASA's path to planetary protection requirements for human exploration missions: Update on recent progress. *in* 2016 IEEE Aerospace Conference, Big Sky, MT, 1–8. doi:10.1109/AERO.2016.7500837.

Jouzel, J., Masson-Delmotte, V., et al., 2007. Orbital and millennial Antarctic climate variability over the past 800,000 years. *Science* **317**, 793-796. doi:10.1126/science.1141038.

Jun, I., Mitrofanov, I., et al., 2013. Neutron background environment measured by the Mars Science Laboratory's Dynamic Albedo of Neutrons instrument during the first 100 sols. *J. Geophys. Res. Planets.* **118**, 2400–2412. doi:10.1002/2013JE004510.

Kahre, M.A., Haberle, R.M., 2010. Mars CO_2 cycle: Effects of airborne dust and polar cap ice emissivity. *Icarus* **207**(2), 648–653. doi:10.1016/j.icarus.2009.12.016.

Kahre, M.A., Murphy, J.R., et al., 2017. The Mars dust cycle, in: Haberle, R.M., Clancy, R.T., Forget, F., Smith, M.D., Zurek, R.W. (Eds.), *The Atmosphere and Climate of Mars*. Cambridge University Press. 229–294. doi:10.1017/9781139060172.010.

Khayat, A.S.J., Smith, M.D., Guzewich, S.D., 2019. Understanding the water cycle above the north polar cap on Mars using MRO CRISM retrievals of water vapor. *Icarus* **321**, 722–735. doi:10.1016/j.icarus.2018.12.024.

Kieffer, H.H., Chase Jr., S.C., Martin, T.Z., Miner, E.D., Palluconi, F.D., 1976. Martian north pole summer temperatures: Dirty water ice. *Science* **194**, 1341–1344. doi:10.1126/science.194.4271.1341.

Kieffer, H.H., 1990. H_2O grain size and the amount of dust in Mars' residual north polar cap. *J. Geophys. Res.* **95**(B2), 1481–1493. doi:10.1029/JB095iB02p01481.

Kieffer, H.H., Titus, T.N., Mullins, K.F., Christensen, P.R., 2000. Mars South polar spring and summer behavior observed by TES: Seasonal cap evolution controlled by frost grain size. J. Geophys. Res. 105(E4), 9653–9699. doi:10.1029/1999JE001136.

Kieffer, H.H., Titus, T.N., 2001. TES mapping of Mars' north seasonal cap. *Icarus* **154**, 162–180. doi:10.1006/icar.2001.6670.

Kieffer, H.H., 2007. Cold jets in the Martian polar caps. *J. Geophys. Res.* **112**, E08005. doi:10.1029/2006JE002816.

Kieffer, H.H., 2013. Thermal model for analysis of Mars infrared mapping. *J. Geophys. Res. Planets* **118**, 451-470. doi:10.1029/2012JE004164.

Kite, E.S., Mischna, M., Gao, P., Yung, Y., 2017. Climate optimum on Mars initiated by atmospheric collapse? *at* 48th Lunar and Planetary Science Conference, Ab. 1747.

Klesh, A., Krajewski, J., 2015. MarCO: Cubesats to Mars in 2016. *at* AIAA/USU Conference on Small Satellites, Ab. SSC15-III-3.

Kliore, A., Fjeldbo, G., Seidel, B.L., Rasool, S.I., 1969. Mariners 6 and 7: Radio Occultation Measurements of the Atmosphere of Mars. *Science* **166**(3911), 1393-1397. doi:10.1126/science.166.3911.1393.

Knak Jensen, S.J., Skibsted, J., et al., 2014. A sink for methane on Mars? The answer is blowing in the wind. *Icarus* **236**, 24–27. doi:10.1016/j.icarus.2014.03.036.

Kneisel, C., Hauck, C., Fortier, R., Moorman, B., 2008. Advances in geophysical methods for permafrost investigations. *Permafrost Periglac. Process.* **19**, 157–178. doi:10.1002/ppp.616.

Kok, J.F., 2010. Difference in the wind speeds required for initiation versus continuation of sand transport on Mars: Implications for dunes and dust storms, *Phys. Rev. Lett.* **104**(7), 074502. doi:10.1103/PhysRevLett.104.074502.

Kok, J.F., Parteli, E.J.R., Michaels, T.I., Karam, D.B., 2012. The physics of wind-blown sand and dust. *Rep. Prog. Phys.* **75,** 106901. doi:10.1088/0034-4885/75/10/106901.

Korablev, O., et al., 2019. No detection of methane on Mars from early ExoMars Trace Gas Orbiter observations. *Nature*, doi:10.1038/s41586-019-1096-4.

Koutnik, M., Byrne, S. and Murray, B., 2002. South polar layered deposits of Mars: The cratering record. *J. Geophys. Res. Planets* **107**(E11), 5100. doi:10.1029/2001JE001805.

Kreslavsky, M.A., Head, J.W., 2002. Mars: Nature and evolution of young latitude-dependent water-ice-rich mantle. *Geophys. Res. Lett.* **29**(15), 14-1–14-4. doi:10.1029/2002GL015392.

Kreslavsky, M., Head, J., Marchant, D., 2008. Periods of active permafrost layer formation during the geological history of Mars: Implications for circum-polar and mid-latitude surface processes. *Planet. Space Sci.* **56**, 289–302.doi:10.1016/j.pss.2006.02.010.

Kvenvolden, K.A., Rogers, B.W., 2005. Gaia's breath – global methane exhalations. *Marine Petrol. Geol.* **22**(4), 579–590. doi:10.1016/j.marpetgeo.2004.08.004.

Lanagan, P.D., McEwen, A.S., Keszthelyi, L.P., Thordarson, T., 2001. Rootless cones on Mars indicating the presence of shallow equatorial ground ice in recent times. *Geophys. Res. Lett.* **28**(12), 2365–2367. doi:10.1029/2001GL012932.

Landis, M.E., Byrne, S., Daubar, I.J., Herkenhoff, K.E., Dundas, C.M., 2016. A revised surface age for the North Polar Layered Deposits of Mars. *Geophys. Res. Lett.* **43**(7), 3060–3068. doi:10.1002/2016GL068434.

Langevin, Y., Poulet, F., Bibring, J.-P., Schmitt, B., Doute, S., Gondet, B., 2005. Summer evolution of the north polar cap of Mars as observed by OMEGA/Mars Express. *Science* **307**(5715), 1581–1584. doi:10.1126/science.1109438.

Langevin, Y., Bibrin, J.-P., et al., 2007. Observations of the south seasonal cap of Mars during recession in 2004–2006 by the OMEGA visible/near-infrared imaging spectrometer on board Mars Express. *J. Geophys. Res.* **112**, E08S12. doi:10.1029/2006JE002841.

Lapalme, C.M., Lacelle, D., Pollard, W., Fortier, D., Davila, A., McKay, C.P., 2017. Cryostratigraphy and the sublimation unconformity in permafrost from an ultraxerous environment, University Valley, McMurdo dry valleys of Antarctica. *Permafrost Periglac. Process.* **28**, 649–662. doi:10.1002/ppp.1948.

Lapotre, M.G.A., Ewing, R.C., Lamb, M.P., Fischer, W.W., Grotzinger, J.P., Rubin, D.M., Lewis, K.W., Ballard, M.J., Day, M., Gupta, S. and Banham, S.G., 2016. Large wind ripples on Mars: A record of atmospheric evolution. *Science* **353**(6294), 55–58. doi:10.1126/science.aaf3206.

Laskar, J., Levrard, B., Mustard, J.F., 2002. Orbital forcing of the Martian polar layered deposits. *Nature* **419**, 375–377. doi:10.1038/nature01066.

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M., Levrard, B., 2004. A long-term numerical solution for the insolation quantities of the Earth. *Astronomy and Astrophysics* **428**, 261–285. doi:10.1051/0004-6361:20041335.

Lefèvre, F., Forget, F., 2009. Observed variations of methane on Mars unexplained by known atmospheric chemistry and physics. *Nature* **460**, 720–723. doi:10.1038/nature082228.

Lefèvre F., 2019. The enigma of methane on Mars. In: Cavalazzi B., Westall F. (Eds.) *Biosignatures for Astrobiology. Advances in Astrobiology and Biogeophysics.* Springer International Publishing. 253–266. doi:10.1007/978-3-319-96175-0_12.

Lefort, A., Russell, P.S., Thomas, N., McEwen, A.S., Dundas, C.M., Kirk, R.L., 2009. Observations of periglacial landforms in Utopia Planitia with the High Resolution Imaging Science Experiment (HiRISE). *J. Geophys. Res.* **114**, E04005, doi:10.1029/2008JE003264.

Lefort, A., Russell, P.S., Thomas, N., 2010. Scalloped terrains in the Peneus and Amphitrites Paterae region of Mars as observed by HiRISE. *Icarus* **205**, 259–268. doi:10.1016/j.icarus.2009.06.005.

Leighton, R.B., Murray, B.C., 1966. Behavior of carbon dioxide and other volatiles on Mars. *Science* **153**(3732), 136–144. doi:10.1126/science.153.3732.136.

Lenoir, B., Banfield, D., Caughey, D.A., 2011. Accommodation study for an anemometer on a Martian lander. *J. Atmos. Oceanic Tech.* **28**(2), 210–218.

Leovy, C.B., Briggs, G.A., Young, A.T., Smith, B.A., Pollack, J.B., Shipley, E.N., R.L. Wildey, 1972. The Martian Atmosphere: Mariner 9 Television Experiment Progress Report. *Icarus* **17**, 373–393. doi:10.1016/0019-1035(72)90006-1.

Leshin, L.A., 2000. Insights into martian water reservoirs from analyses of martian meteorite QUE94201. *Geophys. Res. Lett.* **27**, 2017–2020. doi:10.1019/1999GL008455.

Leshin, L.A., Mahaffy, P.R., et al., 2013. Volatile, isotope, and organic analysis of martian fines with the Mars Curiosity Rover. *Science* **341**(6153),1238937. doi:10.1126/science.1238937.

Levrard, B., Forget, F., Montmessin, F., Laskar, J., 2007. Recent formation and evolution of northern Martian polar layered deposits as inferred from a Global Climate Model. *J. Geophys. Res.* **112**, E06012. doi:10.1029/2006JE002772.

Levy, J., Head, J., Marchant, D., 2009. Thermal contraction crack polygons on Mars: Classification, distribution, and climate implications from HiRISE observations. *J. Geophys. Res.* **114**, E01007. doi:10.1029/2008JE003273.

Lewis, S.R., Barker, P.R., 2005. Atmospheric tides in a Mars general circulation model with data assimilation. *Adv. Space Res.* **36**, 2162–2168. doi:10.1016/j.asr.2005.05.122.

Liu, J., Luo, B., Douté, S., Chanussot, J., 2018. Exploration of planetary hyperspectral images with unsupervised spectral unmixing: A case study of planet Mars. *Remote Sens.* **10**, 737. doi:10.3390/rs10050737.

Määttänen, A., Vehkamäki, H., Lauri, A., Napari, I., Kulmala, M., 2007. Two-component heterogeneous nucleation kinetics and an application to Mars. *J. Chemical Physics* **127,** 134710. doi: 10.1063/1.2770737.

MacGregor, J. A., Fahnestock, M.A., et al., 2016. A synthesis of the basal thermal state of the Greenland Ice Sheet. J. *Geophys. Res. Earth Surf.* **121**, 1328–1350. doi:10.1002/2015JF003803.

Madeleine, J.-B., Forget, F., et al. 2009. Amazonian northern mid-latitude glaciation on Mars: A proposed climate scenario. Icarus, 203, 390–405. doi:10.1016/j.icarus.2009.04.037

Madeleine, J.-B., Head, J.W.,et al., 2014. Recent ice ages on Mars: The role of radiatively active clouds and cloud microphysics. *Geophys. Res. Lett.* **41,** 4873–4879. doi:10.1002/2014GL059861..

Mahaffy, P.R., Webster, C.R., Cabane, et al., 2012. The sample analysis at Mars investigation and instrument suite, Space Sci. Rev. 170, 401–478. doi:10.1007/s11214-012-9879-z.

Mahaffy, P.R., Webster, C.R., Atreya, et al., 2013. Abundance and isotopic composition of gases in the Martian atmosphere from the Curiosity Rover. *Science* **341**, 263–266. doi:10.1126/science.1237966.

Mahaffy, P.R., Webster, C.R., Stern, J.C., al., 2015. The imprint of atmospheric evolution in the D/H of Hesperian clay minerals on Mars. *Science* **347**, 412–414. doi:10.1126/science.1260291.

Malin, M.C., Caplinger, M.A., Davis, S.D., 2002. Observational evidence for an active surface reservoir of solid carbon dioxide on Mars. *Science* **294**, 2146–2148. doi:10.1126/science.1066416.

Malin, M.C., Edgett, K.S., Posiolova, L.V., McColley, S.M., Dobrea, E.Z.N., 2006. Present-day impact cratering rate and contemporary gully activity on Mars. *Science* **314**, 1573–1577. doi:10.1126/science.1135156.

Manning, C.V., Bierson, C., Putzig, N.E., McKay, C.P., 2019. The formation and stability of buried polar CO_2 deposits on Mars. *Icarus* **317**, 509–517. doi:10.1016/j.icarus.2018.07.021.

Martín-Torres, F.J., Zorzano, M.P., Valentín-Serrano, P., Harri, A.M., Genzer, M., Kemppinen, O., Rivera-Valentin, E.G., Jun, I., Wray, J., Madsen, M.B., Goetz, W., 2015. Transient liquid water and water activity at Gale crater on Mars. *Nature Geoscience* **8**(5), 357–361. doi:10.1038/ngeo2412.

Matsuo, K., Heki, K., 2009. Seasonal and inter-annual changes of volume density of martian CO_2 snow from time–variable elevation and gravity. *Icarus* **202**, 90–94. doi:10.1016/j.icarus.2009.02.023.

Max, M.D., Clifford, S.M., Johnson, A.H., 2013. Hydrocarbon system analysis for methane hydrate exploration on Mars, in: Ambrose, W.A., Reilly, J.F., Peters, D.C. (Eds.), Energy resources for human settlement in the solar system and Earth's future in space. *American Assoc. Petroleum Geologists* **101**, 99–114. doi:10.1306/13361573M1013546.

McCleese, D. J. et al., 2010. Structure and dynamics of the Martian lower and middle atmosphere as observed by the Mars Climate Sounder: Seasonal variations in zonal mean temperature, dust, and water ice aerosols. *J. Geophys. Res.* **115**(E12), 1–16. doi:10.1029/2010JE003677.

McEwen, A.S., Ojha, L., et al., 2011. Seasonal flows on warm Martian slopes. *Science* **333**, 740–743. doi:10.1126/science.1204816.

Mellon, M.T., Jakosky, B.M., 1993. Geographic variations in the thermal and diffusive stability of ice on Mars, *J. Geophys. Res.* **98**, 3345–3364. doi:10.1029/92JE02355.

Mellon, M.T., Jakosky, B.M., 1995. The distribution and behavior of Martian ground ice during past and present epochs. *J. Geophys. Res.* **100**, 11781–11799. doi:10.1029/95JE01027.

Mellon, M.T., Feldman, W.C., Prettyman, T.H., 2004. The presence and stability of ground-ice in the southern hemisphere of Mars. *Icarus* **169**, 324–340. doi:10.1016/j.icarus.2003.10.022.

Mellon, M.T., Arvidson, R.E., Marlow, J.J., Phillips, R.J., Asphaug, E., 2008. Periglacial landforms at the Phoenix landing site and the northern plains of Mars. *J. Geophys. Res.* **113**, E00A23. doi:10.1029/2007JE003039.

Mellon M. T., Arvidson, R.E., Sizemore, et al., 2009. Ground ice at the Phoenix landing site: Stability state and orgin. J. Geophys. Res. 114, E00E07. doi:10.1029/2009JE003417.

MEPAG, 2018. Mars scientific goals, objectives, investigations, and priorities. Banfield, D. (Ed.), 81 pp. https://mepag.jpl.nasa.gov/reports/MEPAG%20Goals_Document_2018.pdf.

MEPAG, 2015. Report from the Next Orbiter Science Analysis Group (NEX-SAG). Campbell, B., Zurek, R. (Chair). 77pp. https://mepag.jpl.nasa.gov/reports/NEX-SAG_draft_v29_FINAL.pdf.

Milkovich, S.M., Head, J.W., 2005. North polar cap of Mars: Polar layered deposit characterization and identification of a fundamental climate signal. *J. Geophys. Res.* **110**, E01005. doi:10.1029/2004JE002349.

Miller, J.L., Hibbitts, C.A., Mellon, M.T., Sizemore, H.G., 2019. Salt and water migration in Mars-like permafrost soils. *at* 50th Lunar and Planetary Science Conference, Ab. 3077.

Milliken, R.E., Mustard, J.F., 2003. Erosional morphologies and characteristics of latitude-dependent surface mantles on Mars. *at* Sixth International Conference on Mars, Ab. 3240.

Minitti, M.E., Hamilton, V.E., 2010. A search for basaltic-to-intermediate glasses on Mars: Assessing martian crustal mineralogy. *Icarus* **210**, 135–149. doi:10.1016/j.icarus.2010.06.028

Mischna, M.A., Richardson, M.I., Wilson, R.J., McCleese, D.J., 2003. On the orbital forcing of Martian water and CO_2 cycles: A general circulation model study with simplified volatile schemes. *J. Geophys. Res.* **108**(E6), 5062. doi:10.1029/2003JE002051.

Mischna, M.A., Smith, M., Kursinski, R., Banfield, D., 2009. Atmospheric science research priorities for Mars. *White Paper submitted to* NRC Decadal Survey, 2011-2020. https://mepag.jpl.nasa.gov/reports/decadal/Atmospheric_Science_White_Paper_FINAL.pdf .

Montmessin, F., Smith, M.D., Langevin, Y., Mellon, M.T., Fedorova, A., 2017. The Water Cycle, in: Haberle, R.M., Clancy, R.T., Forget, F., Smith, M.D., Zurek, R.W. (Eds.), *The atmosphere and climate of Mars*. Cambridge University Press. 338–373. doi:10.1017/9781139060172.011.

Moores, J.E., Gough, R.V., Martinez, G.M., Meslin, P.-Y., Smith, C.L., Atreya, S.K., Mahaffy, P.R., Newman, C.E., Webster, C.R., 2019. Methane seasonal cycle at Gale Crater on Mars consistent with regolith adsorption and diffusion. *Nature Geoscience*, *in press*. doi:10.1038/s41561-019-0313-y.

Morgenstern, A., Hauber, E., et al., 2007. Deposition and degradation of a volatile-rich layer in Utopia Planitia and implications for climate history of Mars. *J. Geophys. Res.* **112**, E06010. doi:10.1029/2006JE002869.

Morgan, G.A., Putzig, N.E., Perry, M.R., Bramson, A.M., (2019). The Mars Subsurface Water Ice Mapping (SWIM) Project. *at* 50th Lunar and Planetary Science Conference, Ab. 2918.

Mumma, M.J., Villanueva, G.L., Novak, R.E., Hewagame, T., Bonev, B.P., DiSanti, M.A., Mandell, A.M., Smith, M.D., 2009. Strong release of methane on Mars in northern summer 2003. *Science* **323**, 1041–1045.

Murray, B.C., Soderblom, L.A., et al., 1972. Geological framework of the South polar region of Mars. *Icarus* **17**, 328–345. doi:10.1016/0019-1035(72)90004-8.

Mustard, J.F., Cooper, C.D., Rifkin, M.K., 2001. Evidence for recent climate change on Mars from the identification of youthful near-surface ground ice. *Nature* **412**, 411–414. doi: 10.1038/35086515.

Navarro, T., Madeleine, J.-B., Forget, F., Spiga, A., Millour, E., Montmessin, F., Määttänen, A., 2014. Global climate modeling of the Martian water cycle with improved microphysics and radiatively active water ice clouds, *J. Geophys. Res. Planets* **119**, 1479–1495. doi:10.1002/2013JE004550.

Nerozzi, S., Holt, J.W., 2018. Earliest accumulation history of the north polar layered deposits, Mars from SHARAD. Icarus 308, 128–137. doi:10.1016/j.icarus.2017.05.027.

Newman, C.E., Lewis, S.R., Read, P.L., Forget, F., 2002. Modeling the martian dust cycle 2. Multiannual radiatively active dust transport simulations. *J. Geophys. Res.* **107**(E12), 5124. doi:10.1029/2002JE001920.

Newman, C.E., Lewis, S.R., Read, P.L., 2005. The atmospheric circulation and dust activity in different orbital epochs on Mars. *Icarus* **174**, 135–160. doi:10.1016/j.icarus.2004.10.023.

Newman, C.E., Gómez-Elvira, J., Marin, M., Navarro, S., Torres, J., Richardson, M.I., Battalio, J.M., Guzewich, S.D., Sullivan, R., de la Torre, M., Vasavada, A.R., 2017. Winds measured by the Rover Environmental Monitoring Station (REMS) during the Mars Science Laboratory (MSL) rover's Bagnold Dunes Campaign and comparison with numerical modeling using MarsWRF. *Icarus* **291**, 203–231. doi:10.1016/j.icarus.2016.12.016.

Newman, C.E., Viudex-Moreiras, D., et al., 2019, The observed winter circulation at Insight's landing site and its impact on understanding the year-round circulation and aeolian activity in Elysium Planitia and Gale Crater. *at* 50th Lunar and Planetary Science Conference, Ab. 2302.

Noguchi, K., Morii, Y., Oda, N., Kuroda, T., Tellmann, S. and Pätzold, M., 2017. Role of stationary and transient waves in CO2 supersaturation during northern winter in the Martian atmosphere revealed by MGS radio occultation measurements. *J. Geophys. Res. Planets* **122**(5), 912–926. doi:10.1002/2016JE005142.

Noguchi, K., Ikeda, S., Kuroda, T., Tellmann, S., Pätzold, M., 2014. Estimation of changes in the composition of the Martian atmosphere caused by CO_2 condensation from GRS Ar measurements and its application to the rederivation of MGS radio occultation measurements. *J. Geophys. Res. Planets* **119**(12), 2510–2521. doi:10.1002/2014JE004629.

Nuding, D.L., Rivera-Valentin, et al., 2014. Deliquescence and efflorescence of calcium perchlorate: An investigation of stable aqueous solutions relevant to Mars. *Icarus* **243**, 420–428. doi:10.1016/j.icarus.2014.08.036.

Nuding, D.L., Davis, R.D., Gough, R.V., Tolbert, M.A., 2015. The aqueous stability of a Mars salt analog: Instant Mars. *J. Geophys. Res. Planets* **120**, 588–598. doi:10.1002/2014JE004722.

Obbard, R.W., Troderman, G., Baker, I., 2009. Imaging brine and air inclusions in sea ice using micro-X-ray computed tomography. *J. Glaciology* **55**(194), 1113–1115. doi:10.3189/002214309790794814.

Oehler, D.Z., Allen, C.C., 2010. Evidence for pervasive mud volcanism in Acidalia Planitia, Mars. *Icarus* **208**, 636–657. doi:10.1016/j.icarus.2010.03.031.

Oehler, D.Z., Etiope, G., 2017. Methane seepage on Mars: Where to look and why. *Astrobiology* **17**(12), 1233–1264, doi: 10.1089/ast.2017.1657.

Ojha, L., Lewis, K., 2018. The density of the Medusae Fossae Formation: Implications for its composition , origin , and importance in Martian history. *J. Geophys. Res. Planets* **123**, 1368–1379, doi:10.1029/2018JE005565.

Ojha, L., Nerozzi, S., Lewis, K.W., 2019. Constraints on the Density of the Martian North Polar Cap from Gravity and Topography. *at* 50th Lunar and Planetary Science Conference, Ab. 2712.

Orosei, R., Lauro, S.E., et al., 2018. Radar evidence of subglacial liquid water on Mars. *Science* **361**, 490–493. doi:10.1126/science.aar7268.

Owen, T., Maillard, J.P., de Bergh, C., Lutz, B.L., 1988. Deuterium on Mars: The abundance of HDO and the value of D/H. *Science* **240**, 1767.

Paige, D.A., Wood, S.E., 1992. Modeling the Martian seasonal CO_2 cycle 2. Interannual variability. *Icarus* **99**, 15–27. doi:10.1016/0019-1035(92)90167-6.

Paige, D. A., 1992. The thermal stability of near-surface ground ice on Mars. *Nature* **356**, 43–45. doi:10.1038/356043a0.

Pasquon, K., Gargani, J., Masse, M., Conway, S. J., 2016. Present-day formation and seasonal evolution of linear dune gullies on Mars. *Icarus* **274,** 195–210. doi:10.1016/j.icarus.2016.03.024.

Pathare, A.V., Feldman, W.C., Prettyman, T.H., Maurice, S., 2018. Driven by excess? Climatic implications of new global mapping of near-surface water-equivalent hydrogen on Mars. *Icarus* **301**, 97–116. doi: 10.1016/j.icarus.2017.09.031.

Pätzold, M., Häusler, B., Tyler, G.L., Andert, T., Asmar, S.W., Bird, M.K., Dehant, V., Hinson, D.P., Rosenblatt, P., Simpson, R.A., Tellmann, S., 2016. Mars Express 10 years at Mars: observations by the Mars Express radio science experiment (MaRS). *Planet. Space Sci.* **127**, 44–90. doi:10.1016/j.pss.2016.02.013.

Perron, J.T., Huybers, P., 2009. Is there an orbital signal in the polar layered deposits on Mars? *Geology* **37**, 155–158. doi:10.1130/G25143A.1.

Pettengill, G. H., Ford, P. G., 2000. Winter clouds over the north Martian polar cap, *Geophys. Res. Lett*. **27**, 609–612.

Phillips, R.J., Zuber, M.T., et al., 2008. Mars north polar deposits: Stratigraphy, age, and geodynamical response. *Science* **320**, 1182–1185. doi:10.1126/science.1157546.

Phillips, R.J., Davis, B.J., et al., 2011. Massive CO_2 ice deposits sequestered in the south polar layered deposits of Mars. *Science* **332**, 838–841. doi:10.1126/science.1203091.

Picardi, G., Plaut, J.J., et al., 2005. Radar soundings of the subsurface of Mars. *Science* **310**, 1925–1928. doi:10.1126/science.1122165.

Pilgrim, R., Ulrich, R., Leftwich, M., 2009. Subsurface spectroscopic probe for regolith analysis. *at* 40th Lunar and Planetary Science Conference, Ab. 1219.

Piqueux, S., Byrne, S., Richardson, M.I., 2003. Sublimation of Mars' southern seasonal CO_2 ice cap and the formation of spiders. *J. Geophys. Res.* **108**(E8), 5084. doi:10.1029/2002JE002007.

Piqueux, S., Kleinbohl, A., Hayne, P.O., Kass, D.M., Schofield, J.T., McClees, D.J., 2015. Variability of the martian seasonal CO_2 cap extent over eight Mars Years. *Icarus* **251**, 164–180. doi:10.1016/j.icarus.2014.10.045.

Plaut, J.J., Picardi, G., et al., 2007. Subsurface radar sounding of the south polar layered deposits of Mars. *Science* **316**, 92–95. doi:10.1126/science.1139672.

Plaut, J.J., Safaeinili, A., et al.., 2009. Radar evidence for ice in lobate debris aprons in the mid-northern latitudes of Mars. *Geophys. Res. Lett.* **36**, L02203. doi:10.1029/2008GL036379.

Pommerol, A., Schmitt, B., Beck, P., Brissaud, O., 2009. Water sorption on martian regolith analogs: Thermodynamics and near-infrared reflectance spectroscopy. *Icarus* **204**, 114–136. doi:10.1016/j.icarus.2009.06.013.

Pommerol, A., Thomas, N., et al., 2011. Photometry and bulk physical properties of Solar System surfaces icy analogs: The Planetary Ice Laboratory at University of Bern. *Planet. Space Sci.* **59**(13), 1601–1612. doi:10.1016/j.pss.2011.07.009.

Portyankina, G., Hansen, C.J., Aye, K.-M., 2017. Present-day erosion of Martian polar terrain by the seasonal CO_2 jets. *Icarus* **282**, 93–103. doi:10.1016/j.icarus.2016.09.007.

Portyankina, G., Merrison, et al., 2019. Laboratory investigations of the physical state of CO_2 ice in a simulated Martian environment. *Icarus* **322**, 210–220. doi:10.1016/j.icarus.2018.04.021.

Prettyman, T. H., Feldman, W.C., et al., 2004. Composition and structure of the Martian surface at high southern latitudes from neutron spectroscopy. *J. Geophys. Res.* **109**, E05001. doi:10.1029/2003JE002139.

Price, P.B., 2007. Microbial life in glacial ice and implications for a cold origin of life. *FEMS Microbiology Ecology* **59**(2), 217–231. doi:10.1111/j.1574-6941.2006.00234.x.

Primm, K.M., Stillman, D.E., 2019. Investigating the Hysteretic Behavior of Mars-Relevant Salts. *at* 50th Lunar and Planetary Science Conference, Ab. 1291.

Priscu, J.C., Christner, B.C., 2004. Earth's icy biosphere. *in* Bull, A.T. (Ed.), *Microbial Diversity and Bioprospecting*. ASM Press, Washington, D.C., 130–145.

Pustovalov, A., Gusev, V., Borshchevsky, A., Chmielewski, A. 1999. Experimental confirmation of Powerstick concept. *NASA Technical Reports Service*, document ID 20000054690.

Putzig, N.E., Philips, et al., 2009.Subsurface structure of Planum Boreum from Mars Reconnaissance Orbiter Shallow Radar soundings. *Icarus* **204**, 443–457. doi:10.1016/j.icarus.2009.07.034.

Putzig, N.E., Phillips, et al., 2014. SHARAD soundings and surface roughness at past, present, and proposed landing sites on Mars: Reflections at Phoenix may be attributable to deep ground ice. *J. Geophys. Res. Planets* **119**, 1936–1949. doi:10.1002/2014JE004646.

Putzig, N.E., Smith, I.B., et al., 2018. Three-dimensional radar imaging of structures and craters in the Martian polar caps. *Icarus* **308**, 138–147. doi:10.1016/j.icarus.2017.09.023.

Putzig, N.E., Diniega, S., et al., 2019. Results from the Ice and Climate Evolution Science Analysis Group (ICE-SAG). *at* 50th Lunar and Planetary Science Conference, Ab. 2035.

Rafkin, S.C.R., Haberle, R.M., Banfield, D., Barnes, J., 2009. The value of landed meteorological investigations on Mars: The next advance for climate science. *White Paper submitted to* NRC Decadal Survey, 2011-2020. https://mepag.jpl.nasa.gov/reports/decadal/SfcMet_17July2009_3.pdf.

Rampe, E.B., Kraft, M.D., et al., 2012. Allophane detection on Mars with Thermal Emission Spectrometer data and implications for regional-scale chemical weathering processes. *Geology* **40**, 995–998. doi:10.1130/G33215.1.

Rhode, R.A., Price, P.B., 2007. Diffusion-controlled metabolism for long-term survival of single isolated microorganisms trapped within ice crystals. *Proc. Natl. Acad. Sci.* **104**(42), 16592–16597. doi:10.1073/pnas.0708183104.

Richardson, M.I., Mischna, M.A., 2005. Long-term evolution of transient liquid water on Mars. *J. Geophys. Res.* **110**, E03003. doi:10.1029/2004JE002367.

Rivera-Valentín, E.G., Gough, R.V., et al., 2018. Constraining the potential liquid water environment at Gale Crater, Mars. *J. Geophys. Res. Planets* **123**, 1156–1167. doi:10.1002/2018JE005558.

Rummel, J. D., Beaty, D.W., et al., 2014. A new analysis of Mars "Special Regions": Findings of the second MEPAG Special Regions Science Analysis Group (SR-SAG2). *Astrobiology* **14**, 887–965. doi:10.1089/ast.2014.1227.

Russell, P., Thomas, N., et al., 2008. Seasonally active frost-dust avalanches on a north polar scarp of Mars captured by HiRISE. *Geophys. Res. Lett.* **35**, L23204. doi:10.1029/2008GL035790.

Ryan, J.A., Sharman, R.D., Lucich, R.D., 1982. Mars water vapor, near-surface. *J. Geophys. Res.* **87**, 7279–7284.

Santiago-Materese, D.L., Iraci, L.T., Clapham, M.E., Chuang, P.Y., 2018. Chlorine containing salts as water ice nucleating particles on Mars. *Icarus* **202**, 280–287. doi:10.1016/j.icarus.2017.11.001

Schofield, J.T., Barnes, J.R., Crisp, D., Haberle, R.M., Larsen, S., Magalhães, J.A., Murphy, J.R., Seiff, A., Wilson, G., 1997. The Mars Pathfinder Atmospheric Structure Investigation/Meteorology (ASI/MET) Experiment. *Science* **278**(5344), 1752–1758. doi:10.1126/science.278.5344.1752.

Schon, S.C., Head, J.W., Milliken, R.E., 2009. A recent ice age on Mars: Evidence for climate oscillations from regional layering in mid-latitude mantling deposits. *Geophys. Res. Lett.* **36**, L15202. doi:10.1029/2009GL038554.

Schorghofer, N., Aharonson, O., 2005. Stability and exchange of subsurface ice on Mars. *J. Geophys. Res.* **110**, E05003. doi:10.1029/2014JE002350.

Schorghofer, N., Forget, F., 2012. History and anatomy of subsurface ice on Mars. *Icarus* **220**, 1112–1120. doi:10.1016/j.icarus.2012.07.003.

Schulter, T., Arteaga, A., et al., 2017. Deep Space 9 Mission Concept -- Secondary payload study for the proposed Next Mars Orbiter. *at* Low Cost Planetary Missions Conference, Pasadena, CA, Ab. SESS05-02.

Searls, M.L., Mellon, M.T., Martinez-Alonso, S., the HiRISE Team, 2008. Slope analysis and ice stability of the mid-latitude dissected terrain on Mars. *at* 39th Lunar and Planetary Science Conference, Ab. 2376.

Selvans, M.M., Plaut, J.J., Aharonson, O., Safaeinili, A., 2010. Internal structure of Planum Boreum, from Mars advanced radar for subsurface and ionospheric sounding data. *J. Geophys. Res.* **115**, E09003. doi:10.1029/2009JE003537.

Seu, R., Phillips, R.J., Alberti, G., et al., 2007. Accumulation and erosion of Mars' south polar layered deposits. *Science* **317**, 1715–1718. doi:10.1126/science.1144120.

Sizemore, H.G., Mellon, M.T., 2006. Effects of soil heterogeneity on martian ground-ice stability and orbital estimates of ice table depth. *Icarus* **185**, 358–369. doi:10.1016/j.icarus.2006.07.018.

Sizemore, H.G., Mellon, M.T., 2008. Laboratory characterization of the structural properties controlling dynamical gas transport in Mars-analog soils. *Icarus* **197**, 606–620. doi:10.1016/j.icarus.2008.05.013.

Sizemore, H.G., Mellon, M.T., Golombek, M.P., 2009. Ice table depth variability near small rocks at the Phoenix landing site, Mars: A pre-landing assessment. *Icarus* **199**, 303–309. doi:10.1016/j.icarus.2008.10.008.

Sizemore, H.G., Mellon, M.T., et al., 2010. In situ analysis of ice table depth variations in the vicinity of small rocks at the Phoenix landing site. *J. Geophys. Res.* **115**, E00E09. doi:10.1029/2009JE003414.

Sizemore, H. G., Zent, A.P., Rempel, A.W., 2015. Initiation and growth of martian ice lenses. *Icarus* **251**, 191–210. doi:10.1016/j.icarus.2014.04.013.

Sklute, E.C., Rogers, A.D., et al., 2018. Amorphous salts formed from rapid dehydration of multicomponent chloride and ferric sulfate brines: Implications for Mars. *Icarus* **302**, 285–295. doi:10.1016/j.icarus.2017.11.018.

Smith, I.B., Spiga, A., Holt, J.W., 2015. Aeolian processes as drivers of landform evolution at the South Pole of Mars. *Geomorphology* **240**, 54–69. doi:10.1016/j.geomorph.2014.08.026.

Smith, I.B., Putzig, N.E., Holt, J.W., Phillips, R.J., 2016. An ice age recorded in the polar deposits of Mars. *Science* **352**, 1075–1078. doi:10.1126/science.aad6968.

Smith, I.B., S. Diniega, D.W. Beaty, T. Thorsteinsson, P. Becerra, A.M. Bramson, S.M. Clifford, C.S. Hvidberg, G. Portyankina, S. Piqueux, A. Spiga, and T.N. Titus, (2018a). 6th International Conference on Mars Polar Science and Exploration: Conference summary and five top questions. *Icarus, Mars Polar Science VI special issue,* **308**, 2–14. doi:10.1016/j.icarus.2017.06.027.

Smith, I.B., Hayne, P., et al., 2018b. Unlocking the climate record stored within Mars' polar layered deposits. *Keck Institute for Space Studies, California Institute of Technology.* http://www.kiss.caltech.edu/final_reports/Polar_Final_Report.pdf.

Smith, M. D., 2002. The annual cycle of water vapor on Mars as observed by the Thermal Emission Spectrometer. *J. Geophys. Res*. **107** (E11), 5115. doi:10.1029/2001JE001522.

Smith, M.D., Pearl, J.C., Conrath, B.J., Christensen, P.R., 2001. Thermal Emission Spectrometer results: Mars atmospheric thermal structure and aerosol distribution. *J. Geophys. Res. Planets* 106(E10), 23929–23945. doi:10.1029/2000JE001321.

Smith, M.D., 2008. Spacecraft observations of the martian atmosphere. *Ann. Rev. Earth Planet. Sci.* **36**, 191-219, doi:10.1146/annurev.earth.36.031207.124334.

Smith, P.H., Tamppari, L.K., et al., 2009. H_2O at the Phoenix landing site. *Science* **325**, 58–61. doi:10.1126/science.1172339.

Smith, S.A., Smith, B.A., 1972. Diurnal and seasonal behavior of discrete white clouds on Mars. *Icarus* **16**, 509–521. doi:10.1016/0019-1035(72)90097-8.

Smoluchowski, R., 1968. Mars: Retention of ice. *Science* **159**, 1348–1350. doi:10.1126/science.159.3821.1348.

Soare, R.J., Osinski, G.R., Roehm, C.L., 2008. Thermokarst lakes and ponds on Mars in the very recent (late Amazonian) past. *Earth Planet Sci. Lett.* **272**, 382–393. doi:10.1016/j.epsl.2008.05.010.

Soare, R.J., Conway, S.J., Dohm, J.M., El-Maarry, M.R., 2014. Possible open-system (hydraulic) pingos in and around the Argyre impact region of Mars. *Earth Planet. Sci. Lett.* **398**, 25–36. doi:10.1016/j.epsl.2014.04.044.

Sonnabend, G., Sornig, M., Krötz, P.J., Schieder, R.T., Fast, K.E., 2006. High spatial resolution mapping of Mars mesospheric zonal winds by infrared heterodyne spectroscopy of CO_2. *Geophys. Res. Lett.* **33**, L18201. doi:10.1029/2006GL026900.

Sonnabend, G., Sornig, M., Kroetz, P., Stupar, D., 2012. Mars mesospheric zonal wind around northern spring equinox from infrared heterodyne observations of CO_2. *Icarus* **217**, 315–321. doi:10.1016/j.icarus.2011.11.009.

Sorbjan, Z., Wolff, M., Smith, M.D., 2009. Thermal structure of the atmospheric boundary layer on Mars based on Mini-TES observations. *Quart. J. Royal Met. Soc.* **135**, 1776–1787. doi:10.1002/qj.510.

Sori, M.M., Bramson, A.M., 2019. Water on Mars, with a grain of salt: Local heat anomalies are required for basal melting of ice at the south pole today. *Geophys. Res. Lett.* **46**, 1222–1231. doi:10.1029/2018GL080985.

Sori, M.M., Perron, J.T., Huybers, P., Aharonson, O., 2014. A procedure for testing the significance of orbital tuning of the Martian polar layered deposits. *Icarus* **235,** 136–146. doi:10.1016/j.icarus.2014.03.009.

Spry, J. A., Zalucha, A., Fenton, L., 2017. Planetary protection considerations of Mars dust in the context of current human exploration concepts. *at* 47th International Conference on Environmental Systems (ICES), Ab. ICES-2017-285.

Staehle, R. et al., 2015. Multiplying Mars lander opportunities with $MARS_{DROP}$ microlanders. *at* 29th Annual AIAA/USU Conference on Small Satellites, Ab. SSC15-XI-3.

Steele, L.J., Lewis, S.R., Patel, M.R., 2014. The radiative impact of water ice clouds from a reanalysis of Mars Climate Sounder data. *Geophys. Res. Lett.* **41**, 4471–4478. doi:10.1002/2014GL060235.

Steele, L.J., Balme, M.R., Lewis, S.R., 2017. Regolith-atmosphere exchange of water in Mars' recent past. *Icarus* **284**, 233–248. doi:10.1016/j.icarus.2016.11.023.

Stibal, M., Sabacka, M., Zarsky, J., 2012. Biological processes on glacier and ice sheet surfaces. *Nature Geoscience* **5**, 771–774. doi:10.1038/ngeo1611.

Stillman, D.E., R.E. Grimm, 2010. Dielectric signatures of adsorbed and salty liquid water at the Phoenix landing site, Mars. *J. Geophys. Res.* **116**, E09005. doi:10.1029/2011JE003838.

Stillman, D.E., Michaels, T.I., Grimm, R.E., 2017. Characteristics of the numerous and widespread recurring slope lineae (RSL) in Valles Marineris, Mars. *Icarus* **285**, 195–210. doi:10.1016/j.icarus.2016.10.025.

Stillman, D.E., Grimm, R.E., 2018. Two pulses of seasonal activity in Martian southern mid-latitude recurring slope lineae (RSL). *Icarus* **302**, 126–133. doi:10.1016/j.icarus.2017.10.026.

Stillman, D.E., Primm, K.P., et al., 2019. Magnetic resonance and dielectric spectroscopy investigations of liquid vein networks within ice and ice-regolith mixtures. *at* 50th Lunar and Planetary Science Conference, Ab. 2537.

Stuiver, M., Grootes, P.M., 2000. GISP2 oxygen isotope ratios. *Quaternary Res.* **53**(3), 277–284. doi:10.1006/qres.2000.2127.

Stuurman, C.M., Osinski, G.R., et al., 2016. SHARAD detection and characterization of subsurface water ice deposits in Utopia Planitia, Mars. *Geophys. Res. Lett.* **43**, 9484–9491. doi:10.1002/2016GL070138.

Sullivan, R., Greeley, R., Kraft, M., Wilson, G., Golombek, M., Herkenhoff, K., Murphy, J., Smith, P., 2000. Results of the Imager for Mars Pathfinder windsock experiment. *J. Geophys. Res.* **105**(E10), 24547–24562. doi:10.1029/1999JE001234.

Sullivan, R., Kok, J.F., 2017. Aeolian saltation on Mars at low wind speeds. *J. Geophys. Res. Planets* **122**, 2111–2143. doi:10.1002/2017JE005275.

Svensson, A., Nielsen, S.W., et al., 2005. Visual stratigraphy of the North Greenland Ice Core Project (NorthGRIP) ice core during the last glacial period. *J. Geophys. Res.* **110**, D02108. doi:10.1029/2004JD005134.

Tamppari, L.K., Zurek, R.W., Paige, D.A., 2000. Viking-era water-ice clouds. *J. Geophys. Res.* **105**, 4087– 4107. doi:10.1029/1999JE001133.

Tamppari, L.K., Bass, D., et al., 2010. Phoenix and MRO coordinated atmospheric measurements. *J. Geophys. Res*. **115**, E00E17. doi:10.1029/2009JE003415.

Tamppari L.K., Livesey, N.J., Abshire, J.B., Colaprete, A., Diner, D.J., Feldman, S., Guzewich, S., Mischna, M., Smith, M.D., 2018. An Assessment of Martian Atmospheric Wind Measurement Techniques: A Workshop Report. *at* American Geophysical Union Fall Meeting, Ab. #P43L-3916.

Tanaka, K.L., Kolb, E.J., 2001. Geologic history of the polar regions of Mars based on Mars Global Surveyor data: I. Noachian and Hesperian periods. *Icarus* **154**, 3–21. doi:10.1006/icar.2001.6675.

Tanaka, K.L., Rodriguez, J.A.P., Skinner Jr., J.A., Bourke, M.C., Fortezzo, C.M., Herkenhoff, K.E., Kolb, E.J., Okubo, C.H., 2008. North polar region of Mars: Advances in stratigraphy, structure, and erosional modification. *Icarus* **196**, 318–358. doi:10.1016/j.icarus.2008.01.021.

Tanaka, K.L., Fortezzo, C.M., 2012. Geologic map of the north polar region of Mars. *U.S. Geological Survey Scientific Investigations Map 3177*, pamphlet 11p., 1 sheet, scale 1:2,000,000. http://pubs.usgs.gov/sim/3177/.

Tellmann, S., Pätzold, M., Häusler, B., Hinson, D.P., Tyler, G.L., 2013. The structure of Mars lower atmosphere from Mars Express Radio Science (MaRS) occultation measurements. *J. Geophys. Res. Planets* **118**(2), 306–320. doi:10.1002/jgre.20058.

Thomas, P., Squyres, S., Herkenhoff, K., Murray, B., Howard, A., 1992. Polar deposits on Mars, in: Kieffer, H.H., Jakosky, B.M., Snyder, C.W., Matthews, M.S. (Eds.), Mars. University of Arizona Press. Tucson, pp.767–795.

Thomas, C. Malin, M.C., Edgett, K.S., Carr, M.H., Hartmann, W.K., Ingersoll, A.P., James, P.B., Soderblom, L.A., Veverka, J., Sullivan, R., 2000. North–south geological differences between the residual polar caps on Mars. *Nature* **404**, 161–164.

Thomas, P.C., Malin, M.C., James, P.B., Cantor, B.A., Williams, R.M.E., Gierasch, P., 2005. South polar residual cap of Mars: Features, stratigraphy, and changes. *Icarus* **174**, 535–559. doi:10.1016/j.icarus.2004.07.028.

Thomas, P.C., Calvin, W., Cantor, B., Haberle, R., James, P.B., Lee, S.W., 2016. Mass balance of Mars' residual south polar cap from CTX images and other data. *Icarus* **268**, 118–130, doi:10.1016/j.icarus.2015.12.038.

Tillman, J.E., Landberg, L., Larsen, S.E., 1994. The boundary layer of Mars: Fluxes, stability, turbulent spectra, and growth of the mixed layer, *J. Atmos. Sci.* **51**, 1709–1727, doi:10.1175/1520-0469(1994)051<1709:TBLOMF>2.0.CO;2.

Titus, T.N., Kieffer, H.H., Mullins, K.F., Christensen, P.R., 2001. TES premapping data: Slab ice and snow flurries in the Martian north polar night. *J. Geophys. Res.* **106**(E10), 23181–23196. doi:10.1029/2000JE001284.

Titus, T.N. Kieffer, H.H, Christensen, P.R., 2003. Exposed water ice discovered near the South Pole of Mars. *Science* **299**(5609), 1048–1051. doi:10.1126/science.1080497.

Titus, T.N., Byrne, S., Colaprete, A., Forget, F., Michaels, T.I., Prettyman, T.H., 2017. 12. The CO_2 Cycle, in *The Atmosphere and Climate of Mars*, edited by R.M. Haberle, R.T. Clancy, F. Forget, M.D. Smith, R.W. Zurek, Cambridge University Press, Cambridge, United Kingdom, p. 374–404.

Toner, J.D., Catling, D.C., Light, B., 2014. The formation of supercooled brines, viscous liquids, and low-temperature perchlorate glasses in aqueous solutions relevant to Mars. *Icarus* **233**, 36–47. doi:10.1016/j.icarus.2014.01.018

Usui, T., Alexander, C.M.O'D., Wang, J., Simon, J.I., Jones, J.H., 2015. Meteoritic evidence for a previously unrecognized hydrogen reservoir on Mars. *Earth Planet. Sci. Lett.* **410**, 140–151. doi: 10.1016/j.epsl.2014.11.022

Vandaele et al., 2018. Impact of the 2018 global dust storm on Mars atmosphere composition as observed by NOMAD on ExoMars Trace Gas Orbiter. *at* American Geophysical Union Fall Meeting, Ab. P31A-03.

Vaniman, D.T., Bish, D.L., Chipera, S.J., Fialips, C.I., Carey, J.W., Feldman, W.C., 2004. Magnesium sulphate salts and the history of water on Mars. *Nature* **431**, 663–665. doi:10.1038/nature02973.

Vaniman, D.T., Chipera, S.J., 2006. Transformations of Mg- and Ca-sulfate hydrates in Mars regolith. *American Mineralogist* **91**(10), 1628–1642. doi:10.2138/am.2006.2092.

Villanueva, G.L., Mumma, M.J., Novak, R.E., Hewagama, T., Bonev, B.P., DiSanti, M.D., 2008. Mapping the D/H of water on Mars using high-resolution spectroscopy. *At* 3rd International Workshop on the Mars Atmosphere: Modeling and Observation, Ab. 9101.

Villanueva, G.L., Mumma, M.J., Novak, R.E., Käufl, H.U., Hartogh, P., Encrenaz, T., Tokunaga, A., Khayat, A., Smith, M.D., 2015. Strong water isotopic anomalies in the martian atmosphere:

Probing current and ancient reservoirs. *Science* **348**(6231), 218–221. doi:10.1126/science.aaa3630.

Vincendon, M., Langevin, et al., 2008. Dust aerosols above the south polar cap of Mars as seen by OMEGA. *Icarus* **196**, 488–505. doi:10.1016/j.icarus.2007.11.034.

Vincendon, M., Forget, F., Mustard, J., 2010. Water ice at low to midlatitudes on Mars. *J. Geophys. Res.* **115**, E10001. doi:10.1029/2010JE003584.

Viola, D., McEwen, A.S., Dundas, C.M., Byrne, S., 2015. Expanded secondary craters in Arcadia Planitia, Mars: Evidence for tens of Myr-old shallow subsurface ice. *Icarus* **248**, 190–204. doi:10.1016/j.icarus.2014.10.032.

Vos, E., Aharonson, O., Schorghofer, N., 2019. Dynamic and isotopic evolution of ice reservoirs on Mars. *Icarus* **324**, 1–7. doi:10.1016/j.icarus.2019.01.018.

V&V, 2011. Visions and Voyages for Planetary Science in the Decade 2013-2022. By the Committee on the Planetary Science Decadal Survey. National Academies Press, Washington, D.C. 382 pages.

Wagstaff, K. L., Titus, T.N., Ivanov, A.B., Castano, R., Bandfield, J.L., 2008. Observations of the north polar water ice annulus on Mars using THEMIS and TES. *Planet. Space Sci.* **56**, 256–265. doi:10.1016/j.pss.2007.08.008.

Wainstein, P.A., Tseung, J.-M.W.B., Moorman, B.J., Stevens, C.W., 2008. Integrating GPR and CCRI techniques: Implications for the identification and mapping of ground ice on Mars. *Mars* **4**, 1–13. doi:10.1555/mars.2008.0001.

Wang, A., Freeman, J.J., Jolliff, B.L., 2009. Phase transition pathways of the hydrates of magnesium sulfate in the temperature range 50°C to 5°C: Implication for sulfates on Mars. J. Geophys. Res. 114, E04010. doi:10.1029/2008JE003266.

Wang, A., Feldman, W.C., Mellon, M.T., Zheng, M., 2013. The preservation of subsurface sulfates with mid-to-high degree of hydration in equatorial regions on Mars. Icarus 226, 980–991. doi:10.1016/j.icarus.2013.07.020.

Wang, H., Ingersoll, A.P., 2002. Martian clouds observed by Mars Global Surveyor Mars Orbiter Camera. *J. Geophys. Res.* **107**(E10), 5078. doi:10.1029/2001JE001815.

Wang, H., Richardson, M.I., 2015. The origin, evolution, and trajectory of large dust storms on Mars during Mars years 24-30 (1999-2011). *Icarus* **251**, 112–127. doi:10.1016/j.icarus.2013.10.033.

Watters, T.R., Campbell, B., et al., 2007. Radar sounding of the Medusae Fossae Formation Mars: equatorial ice or dry, low-density deposits? *Science* **318**, 1125–1128. doi: 10.1126/science.1148112.

Webster, C.R., Mahaffy, P.R., et al., 2013. Isotope ratios of H, C, and O in CO_2 and H_2O of the martian atmosphere. *Science* **341**, 260–263. doi:10.1126/science.1237961.

Webster, C.R., Mahaffy, P.R., et al., 2015. Mars methane detection and variability at Gale Crater. *Science* **347**, 415–417. doi:10.1126/science.1261713.

Webster, C.R., Mahaffy, P.R., et al., 2018. Background levels of methane in Mars' atmosphere show strong seasonal variations. *Science* **360**, 1093–1096. doi:10.1126/science.aaq0131.

Westal, F., Foucher, F., et al., 2015. Biosignatures on Mars: What, where, and how? Implications for the search for martian life. *Astrobiology* **15**(11), 998–1029. doi:10.1089/ast.2015.1374.

Whiteway, J., Daly, M., et al., 2008., Lidar on the Phoenix mission to Mars. *J. Geophys. Res.* **113**, E00A08. doi:10.1029/2007JE003002.

Whiteway, J.A., Komguem, L., et al., 2009. Mars water-ice clouds and precipitation. *Science* **325**(5936), 68–70. doi:10.1126/1172344.

Whiteway, J., Komguem, L., Dickinson, C., 2011. Observations of Mars atmospheric dust and clouds with the Lidar Instrument on the Phoenix Mission. *at* Fourth International Workshop on the Mars Atmosphere: Modelling and Observations.

Whitten, J.L., Campbell, B.A., 2018. Lateral continuity of layering in the Mars south polar layered deposits from SHARAD sounding data. *J. Geophys. Res. Planets* **123**, 1541–1554. doi:10.1029/2018JE005578.

Wieczorek, M.A., 2008. Constraints on the composition of the Martian south polar cap from gravity and topography. *Icarus* **196**(2), 506–517. doi:10.1016/j.icarus.2007.10.026.

Williams, R.M.E., Eby, M.A., Staehle, R.L., Bhartia, R., 2015. $Mars_{DROP}$ microprobe architecture: Broadening the science return and in situ exploration from Mars missions. *at* 46th Lunar and Planetary Science Conference, Ab. 2276.

Williamson, W., A. Mannucci, C. Ao, Radio occultation mission to Mars using Cubesats. *at* Low Cost Planetary Missions Conference, Pasadena, CA, Ab. SESS05-03.

Wilson, J.T., Eke, V.R., et al., 2018. Equatorial locations of water on Mars: Improved resolution maps based on Mars Odyssey Neutron Spectrometer data. *Icarus* **299**, 148–160. doi:10.1016/j.icarus.2017.07.028.

Withers, P., Felici, M., Mendillo, M., Moore, L., Narvaez, C., Vogt, M.F. and Jakosky, B.M., 2018. First Ionospheric Results From the MAVEN Radio Occultation Science Experiment (ROSE). *J. Geophys. Res. Space Physics* **123**(5), 4171–4180. doi:10.1029/2018JA025182.

Wood, S.E., Paige, D.A., 1992. Modeling the martian seasonal CO_2 cycle 1. Fitting the Viking Lander pressure curves. *Icarus* **99,** 1–14. doi:10.1016/0019- 1035(92)90166- 5.

Wood, S.E., Griffiths, S.D., Bapst, J.N., 2012. Mars at low obliquity: perennial CO_2 caps, atmospheric collapse, and subsurface warming. *at* Mars Climate Workshop.

Woolley, R., Barba, N., Gallagher, M., Stamenkovic, V., Giersch, L., Komarek, T., 2018. Enabling interplanetary small spacecraft missions. *at* The 20th Annual Small Payload Rideshare Symposium.

Wordsworth, R., Kalugina, Y., Lokshtanov, S., Vigasin, A., Ehlmann, B., Head, J., Sanders, C., Wang, H., 2017. Transient reducing greenhouse warming on early Mars. *Geophys. Res. Lett.* **44**, 665–671, doi:10.1002/2016GL071766.

Xu, W.Q., Tosca, N.J., McLennan, S.M., Parise, J.B., 2009. Humidity-induced phase transitions of ferric sulfate minerals studied by in situ and ex situ X-ray diffraction. *American Mineralogist* **94**, 1629–1637. doi:10.2138/am.2009.3182.

Yen, A.S., Murray, B.C., Rossman, G.R., 1998. Water content of the Martian soil: Laboratory simulations of reflectance spectra. *J. Geophys. Res.* **103**(E5), 11125–11133. doi:10.1029/98JE00739.

Yung, Y. et al., 2018. Methane on Mars and Habitability: Challenges and Responses. *Astrobiology* **18(**10). doi:10.1089/ast.2018.1917.

Zanetti, M., Hiesinger, H., Reiss, D., Hauber, E., Neukum, G., 2010. Distribution and evolution of scalloped terrain in the southern hemisphere, Mars. *Icarus* **206**, 691-706. doi:10.1016/j.icarus.2009.09.10.

Zent, A.P., Fanale, F.P., Salvail, J.R., Postawko, S.E., 1986. Distribution and state of H_2O in the high-latitude shallow subsurface of Mars. *Icarus* **67**, 19-36. doi:10.1016/0019-1035(86)90171-5.

Zent, A.P., Quinn, R.C., 1995. Simultaneous adsorption of CO_2 and H_2O under Mars-like conditions and application to the evolution of the Martian climate. *J. Geophy. Res.* **100**(E3), 5341–5349. doi:10.1029/94JE01899.

Zent, A.P., Howard, D.J., Quinn, R.C., 2001. H_2O adsorption on smectites: Application to the diurnal variation of H_2O in the Martian atmosphere. *J. Geophys. Res.* **106**(E7), 14667–14674. doi:10.1029/2000JE001394.

Zent, A.P. 2008. A historical search for habitable ice at the Phoenix landing site. *Icarus* **196**, 385–408. doi: 10.1016/j.icarus.2007.12.028.

Zent, A.P., Hecht, M.H., Hudson, T.L., Wood, S.E., Chevrier, V.F., 2016. A revised calibration function and results for the Phoenix mission TECP relative humidity sensor. *J. Geophys. Res. Planets* **121**, 626–651. doi:10.1002/2015JE004933.

Zuber, M.T., Phillips, R.J., Andrews-Hanna, J.C., Asmar, S.W., Konopliv, A.S., Lemoine, F.G., Plaut, J.J., Smith, D.E., Smrekar, S.E., 2007. Density of Mars' South Polar Layered Deposits. *Science* **317**(5845). 1718–1719.

Zurek, R.W., 1981. Inference of dust opacities for the 1977 Martian great dust storms from Viking Lander 1 pressure data. *Icarus* **45**(1), 202–215. doi:10.1016/0019-1035(81)90014-2.

Zurek, R.W., Barnes, J.R., Haberle, R.M., Pollack, J.B., Tillman, J.E., Leovy, C.B., 1992. Dynamics of the atmosphere of Mars, in: Kieffer, H.H., Jakosky, B.M., Snyder, C.W., Matthews, M.S. (Eds.), *Mars*. University of Arizona Press. Tucson, 835–933.