# White Paper Summary of the Final Report from the Ice and Climate Evolution Science Analysis group (ICE-SAG)

The Ice and Climate Evolution Science Analysis Group (ICE-SAG) was convened by the Mars Exploration Program Analysis Group (MEPAG) in fall 2018, with the aims of (1) identifying and prioritizing fundamental science questions related to the recent and ongoing evolution of Mars volatiles and climate, and (2) exploring new mission approaches that could address these high-priority science questions during the coming decade (2023–2032). In this white paper, we summarize the ICE-SAG final report via a selection of report materials and provide broad context for the content of this MEPAG-generated report (which is likely a reference mentioned within a number of other, community-based white papers).

Because this white paper is a summary of the ICE-SAG report, the authors are the same:


| ICE-SAG MEMBERS | INSTITUTION |
|---|---|
| **Serina Diniega (Co-Chair)** | Jet Propulsion Laboratory, California Institute of Technology |
| **Than Putzig (Co-Chair)** | Planetary Science Institute |
| Shane Byrne | University of Arizona |
| Wendy Calvin | University of Nevada – Reno |
| Colin Dundas | U.S. Geological Survey, Astrogeology Science Center |
| Lori Fenton | SETI Institute |
| Paul Hayne | University of Colorado |
| David Hollibaugh Baker | NASA – Goddard Space Flight Center |
| Jack Holt | University of Arizona |
| Christine Hvidberg | University of Copenhagen |
| Melinda Kahre | NASA – Ames Research Center |
| Michael Mischna | Jet Propulsion Laboratory, California Institute of Technology |
| Gareth Morgan | Planetary Science Institute |
| Dorothy Oehler | Planetary Science Institute |
| Anya Portyankina | University of Colorado |
| Deanne Rogers | Stony Brook University |
| Hanna Sizemore | Planetary Science Institute |
| Isaac Smith | Planetary Science Institute and York University |
| Alejandro Soto | Southwest Research Institute |
| Leslie Tamppari | Jet Propulsion Laboratory, California Institute of Technology |
| Timothy Titus | U.S. Geological Survey, Astrogeology Science Center |
| Chris Webster | Jet Propulsion Laboratory, California Institute of Technology |

Serina Diniega (serina.diniega@jpl.nasa.gov; 626-720-7293) is the Corresponding Author.


*Reference for the full ICE-SAG report:* 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.

 

## Context for this White Paper

The Ice and Climate Evolution Science Analysis Group (ICE-SAG) was convened by the Mars Exploration Program Analysis Group (MEPAG) in fall 2018 as part of its preparations for the NASA Planetary Science Decadal Survey for 2023 through 2032. The primary focus of ICE-SAG was to (1) identify and prioritize fundamental science questions related to the recent and ongoing evolution of Mars volatiles and climate, and (2) explore new mission approaches that could address these high-priority science questions during the coming decade (2023–2032). As part of that work, ICE-SAG generated five New Frontiers-class mission concepts and three Small Spacecraft mission concepts. These concepts were not meant to define specific, prioritized mission concepts, but instead were proof-of-concepts used to evaluate (very roughly) cost and engineering/scientific feasibility for addressing specific high-priority objectives. ICE-SAG also highlighted some key areas of technology development and complementary laboratory/modeling studies that would enhance or enable acquisition and interpretation of needed measurements.

The ICE-SAG work was primarily completed between October 2018 and April 2019. To gather and incorporate broad community feedback, interim reports were delivered to the MEPAG Executive Committee in December 2018, to the MEPAG community during a MEPAG virtual meeting (VM4: February 25, 2019), and to the broader community via LPSC poster (March 2019) The final report was released July 8, 2019. Since then, presentations on the content of the ICE-SAG report have been invited to a meeting of "Modern Mars processes" scientists at the 9th International Conference on Mars (July 2019) and to the 7th International Conference on Mars Polar Science and Exploration (January 2020), and the report serves as a reference for a number of proposed and ongoing community-based studies. In particular, during ICE-SAG's work, NASA released a ROSES 2018 call (C.30) for Planetary Mission Concept Studies (PMCS). A few mission concepts similar to those in the New Frontiers (NF)-class that are described in the ICE-SAG report were submitted to this competition, and one similar to ICE-SAG mission concept NF5 (Mars Orbiter for Resources, Ices and Environments (MORIE) with PI Wendy Calvin and Deputy PIs Than Putzig and Jack Holt) was selected. The MORIE study presents a mission concept that would address the climate and geological science of buried ice, composition of climate-signature rock types, polar layer stratigraphy, and ongoing surface changes such as the time-varying thickness of seasonal ice. A second Mars orbiter study selected for PMCS (Mars Orbiters for Surface-Atmosphere-Ionosphere Interactions (MOSAIC) with PI Rob Lillis) also addresses ICE-SAG science goals, largely with atmospheric instrumentation but also including the use of radar imaging and sounding capabilities.

In the following pages, we include a selection of materials from the ICE-SAG final report, so as to provide broad context for the content of this MEPAG-generated report, especially as the ICE-SAG report is likely a reference mentioned within a number of other white papers.

Additionally, here, we comment on how the 2019 ICE-SAG results relate to a more recently announced development within the NASA Mars Exploration Program: In February 2020, NASA's budget request for FY21 included a Moon-to-Mars budget with study of a Mars Ice Mapper (MIM) mission concept[1]. The MIM mission concept, as presented at the recent MEPAG meeting (#38: April 15, 2020), aims to determine the location, character, and extent of accessible ice, potentially involving the use of a Canadian Space Agency L-band radar. While many questions remain open regarding the specific science/human exploration objectives of this mission concept, it is similar

[1] Introduced in the FY21 NASA budget request, based on the U.S. President's budget proposal released in February 2020: https://www.nasa.gov/sites/default/files/atoms/files/fy2021_summary_budget_brief.pdf

to ICE-SAG mission concept NF5 in design, although with a different type of radar and research-focused goals.

In summary, NASA's interest in the MIM, MORIE, and MOSAIC mission concepts and the continued discussion within the Mars community (in particular, the Mars modern/active processes and the polar science communities) of the ICE-SAG science questions and needed measurements demonstrate that the high-priority science mission objectives identified and described within the ICE-SAG final report are important and timely, and that feasible mission concepts to address these objectives during the decade discussed in this Decadal Survey process do exist, over a range of mission cost-classes and implementations.

## Select Content from the ICE-SAG final report, July 2019

### Executive Summary (copied; with added description of the NF & SS concept descriptions)

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 of the final report). 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 pertaining to ice[2] 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 ice deposits 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 and evolution 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

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

address critical gaps in knowledge (§6).

The compelling, high-priority science questions concerning Martian ices and climate presented in this report (§3) are addressable by 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[3] climate history. The ICE-SAG discussed a range of mission concepts spanning all mission 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 are potentially realizable within the cost-cap of NASA's New Frontiers Program:

NF1: A polar lander to investigate the upper 1 m or more of northern layered structure, including a drill or geophysical sounder.

NF2: A polar lander to make in situ observations of the evolution of the seasonal frost[2] layer, including a meteorological station — thus requiring operations through polar night.

NF3: An orbiter and small lander(s) to carry out meteorological monitoring from surface to 80 km over diurnal & annual cycles.

NF4: A mid-latitude lander to investigate the vertical structure of buried water ice, including a drill and geophysical sounder.

NF5: An orbiter to map the distribution, structure, and activity of near-surface ices with InSAR and sounder, and spectral & thermal imagers.

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 discussed options to expand or descope these concepts for other mission classes, and we describe a few smaller stand-alone mission concepts:

SS1: Small lander(s) to measure, in high-spatial and temporal resolution, activity and surface/atmospheric environmental conditions within Recurrent Slope Lineae (RSL) or gullies (i.e., features with known present-day activity and yet-unknown formation mechanisms, and that have been hypothesized to involve present-day liquid water).

SS2: A network of micro-lander(s) to measure polar meteorological conditions, to provide in situ observations of atmospheric circulation and Polar Layered Deposits.

SS3: A constellation of small orbiters to conduct radio occultation measurements, to globally monitor atmospheric temperature and pressure profiles, down to within the Planetary Boundary Layer.

The full suite of example mission concepts discussed in the ICE-SAG report 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<br>Current State of | Recent discoveries and studies of Mars' ice reservoirs have significantly changed our views of ice occurrence on Mars, its role in driving surface |

[3] 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" [Visions & Voyages, 2011: p6-11].

| | |
|---|---|
| Knowledge | 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<br>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<br>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<br>Priority Science Area B: Global distribution & volume of subsurface ice | 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 mapping at sub-meter-scale vertical resolution of the near-subsurface within the uppermost 10 m. |
| 5 / §3.3<br>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<br>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 these 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<br>Priority Science Area E: Potential evidence | 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 |

| | |
|---|---|
| of liquid water | 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<br>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<br>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<br>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<br>Mission Concepts to Address Key Ice & 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<br>Mission Concepts | 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<br>Mission Concepts | 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<br>Mission Concepts | 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<br>Key technology challenges and constraints on Ice & Climate focused Mars missions | 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 near the poles at a specific time of year, and reduction in the cost of delivering payloads to the Martian surface. |
| 16 / §6<br>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. |

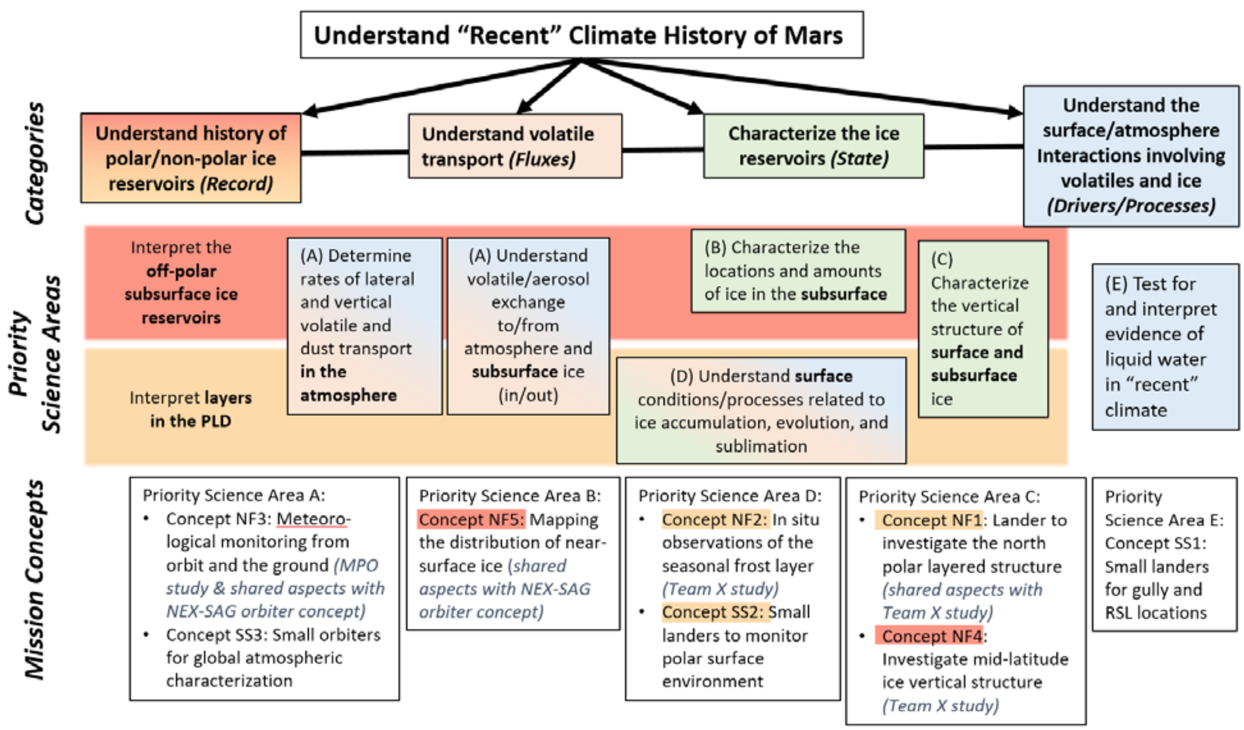


**Figure 4.1.** Figure showing flow from Categories and Priority Science Areas into the Mission Concepts described in the final report. In this schematic, the ICE-SAG main question (top box) divides into four categories of questions (middle row of boxes, boldfaced text). These categories are all highly 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 – listed in Tables 7.1, 7.2). 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).

**Table 7.1.** The science questions within the Priority Science Areas (§3 of the final report) addressed by the mission concepts described within the 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: atmospheric transport of materials | x | x | x | x | x | | x | x |
| Q1: atmospheric controlled exchange of ice/dust – global horizontal/vertical transport | | | x | x | | | | x |
| Q4: annual net mass flux volatiles to/from ice reservoirs | | | x | x | x | | | x |
| Q6: rates of ice/dust deposition/removal on residual polar caps | x | x | x | | | | x | |
| Priority Area B: distribution/volume of water ice | | | | x | x | | | |
| Q8: subsurface water ice location/depth | | | | x | x | | | |
| Q9: subsurface water ice volume/purity | | | | x | x | | | |
| Priority Area C: vertical structure of ice reservoirs | x | | | x | x | | | |
| Q16: constituents in layered ice, that reflect a climate record | x | | | | | | | |
| Priority Area D: surface activity and conditions | x | x | | | | | x | |
| Q19: polar layer formation and modification 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 the report (§4), with the highest priority measurements listed individually.

| **MEASUREMENTS** | NF1 | NF2 | NF3 | NF4 | NF5 | SS1 | SS2 | SS3 |
|---|---|---|---|---|---|---|---|---|
| Priority Area A: atmospheric transport of materials | x | x | x | x | | | x | x |
| M1: wind – global and within Planetary Boundary Layer (PBL) | | | x | | | | | |
| M2: water, dust, temperature, pressure – global and within PBL | | | x | | | | | x |
| Priority Area B: distribution/volume of water ice | | | | x | x | | | |
| M6: high-resolution, regional-to-global map of near-surface structure | | | | | x | | | |
| Priority Area C: vertical structure of ice reservoirs | x | | | x | x | | | |
| M12: characterize layered material as function of depth in polar deposits | x | | | x | | | | |
| Priority Area D: surface activity & conditions | x | x | | | | | x | |
| M16: surface meteorological conditions above an icy layer, through a full Mars year | x | x | | | | | x | |
| Priority Area E: evidence of liquid water | | | | x | x | x | | |