














# Past, Present, and Future of Mars Polar Science: Outcomes and Outlook from the 7th International Conference on Mars Polar Science and Exploration

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## Abstract

Mars Polar Science is a subfield of Mars science that encompasses all studies of the cryosphere of Mars and its interaction with the Martian environment. Every 4 yr, the community of scientists dedicated to this subfield meets to discuss new findings and debate open issues in the International Conference on Mars Polar Science and Exploration (ICMPSE). This paper summarizes the proceedings of the seventh ICMPSE and the progress made since the sixth edition. We highlight the most important advances and present the most salient open questions in the field today, as discussed and agreed upon by the participants of the conference. We also feature agreed-upon suggestions for future methods, measurements, instruments, and missions that would be essential to answering the main open questions presented. This work is thus an overview of the current status of Mars Polar Science and is intended to serve as a road map for the direction of the field during the next 4 yr and beyond, helping to shape its contribution within the larger context of planetary science and exploration.

*Unified Astronomy Thesaurus concepts:* Mars (1007); Planetary climates (2184); Polar caps (1273); Planetary polar regions (1251); Planetary science (1255)


## 1. Introduction and Conference Summary

### 1.1. Context

The history and evolution of ices in the solar system is one of the most active subdisciplines in planetary science, in part due to the relatively rapid timescales of evolution of many icy surfaces, but also because of the importance of water ices for astrobiology and future crewed planetary exploration. On Mars, the repertoire of ices includes massive deposits of highly dynamic carbon dioxide ice, as well as the second-largest (after Earth's) reservoirs of water ice in the inner solar system, found on and beneath its surface. The nature of these Martian ices has fascinated planetary scientists since the first published telescopic observations of bright spots at the Martian poles by Giovanni Cassini in 1666. The first orbital images of the south polar cap were acquired by NASA's

Mariner 7 spacecraft (Masursky et al. 1972), and since then, our understanding of the Martian cryosphere has taken giant leaps. These large increases in knowledge are primarily based on the data returned from Mars-orbiting spacecraft in the past 30 yr, from NASA's MGS<sup>19</sup> (launched in 1996) to ESA's ExoMars TGO (launched in 2016).

Today we know that ice on Mars is exposed in the polar regions (Byrne 2009), buried in the midlatitudinal subsurface (e.g., Boynton et al. 2002), and possibly even present in equatorial locations (e.g., Wilson et al. 2017). In this paper, we will often use the term “Martian cryosphere” to refer to the collection of all of these icy deposits and all aspects of the Martian “frozen realm,” including ancient glaciers, ice sheets, permafrost, seasonal ices, and buried ice, both CO<sub>2</sub> and H<sub>2</sub>O, thus somewhat mimicking the definition of the terrestrial cryosphere given by Marshall (2012). In many ways similar to Earth's, the currently observable Martian cryosphere has

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<sup>19</sup> See Table 1 for a list of acronyms and their definitions used throughout this paper.

interacted with Martian climate over all timescales, ranging from days and months to tens of millions of years, and evidence of ancient glacial processes dating back to nearly the entire history of the planet can be observed on the surface. Furthermore, Mars's ice deposits and their associated landforms may contain information on habitable environments that existed in the past and/or at present day (or even themselves constitute these environments), and they have enormous potential for in situ resource utilization (ISRU) by human exploration in the future. The study of Martian ice is thereby relevant to almost every topic of research in Mars science: from geomorphology (allowing a comparison of landform evolution processes under different conditions across the solar system) to climatology (enabling the understanding of the fundamental mechanisms of climate change) to astrobiology (providing a record of the history of water and, by extension, possible habitable environments on Mars) (see the review/summary papers by Smith et al. 2018, 2020 and Becerra et al. 2020c).

Since 1998, the community dedicated to the study of the Martian cryosphere and its terrestrial analogs has met regularly at the International Conference for Mars Polar Science and Exploration (ICMPSE) to discuss new discoveries, propose new theories, and envision a path forward for what has come to be known as Mars Polar Science. Here, this term encompasses not just the ice at the poles but the entire Martian cryosphere, as well as many aspects of surface-atmosphere interactions. In the present paper, we summarize the current state of Mars Polar Science, focusing on the progress over the past 5 yr, much of which was presented and discussed during the 7th edition of the ICMPSE, held in 2020 January in Ushuaia, Argentina. We also present the most important unresolved issues in the field, as agreed upon by the community at the conference. Naturally, not every development in the field over the past half-decade was presented at the conference. Thus, though we have attempted to include not just the research featured at the meeting but also other recent relevant work, our review reflects primarily the status of Mars Polar Science as it was covered at the 7th ICMPSE.

Past ICMPSE summary papers have acted as a guide for scientists involved in Mars Polar Science and provided input to the discussions and the definition of revised science goals of NASA's Mars Exploration Program Analysis Group (MEPAG 2020). This paper and the 7th ICMPSE come as new decadal and multidecadal planning for planetary science efforts is underway. We thereby hope that our work will serve as a useful update to the road map for achieving the overarching goals and objectives of Mars Polar Science.

### 1.2. Past Editions and Organization of the ICMPSE

The ICMPSE has been held on average every 4 yr since 1998 (during the 6th edition it was decided that a 4 yr frequency would be maintained from that point forward). Each edition has resulted in numerous, sometimes coordinated publications, as well as special editions of journal volumes, and a peer-reviewed paper summarizing the proceedings. The locations, dates, and summary paper citations for each of the conferences are as follows:

1st ICMPSE: Camp Allen, Texas, USA, 1998 October 18–22 (Clifford et al. 2000).

**Table 1**  
Acronyms/Abbreviations and Their Definitions

Acronym	Definition
(N/S) PLD	(North/South) Polar Layered Deposits
(N/S) PRC	(North/South) Polar Residual Cap
BU	Basal Unit
CADIC	Austral Center for Scientific Research (Arg.)
CaSSIS	Colour and Stereo Surface Imaging System
CCF	Concentric Crater Fill
CNSA	China National Space Administration
COMPASS	Climate Orbiter for Mars Polar Atmospheric and Subsurface Science
CONICET	Argentinian National Scientific and Technical Research Council
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
CTX	Context Camera (MRO)
DAF	Dorsa Argentea Formation
DICE	Dielectric, Imagery, and Cryogenic Experiments
DTM	Digital Terrain Model
ESA	European Space Agency
GCM	General/Global Circulation Model
GEL	Global Equivalent Layer
GLF	Glacier-like Form
GMM-3	Goddard Mars Model 3
GPR	Ground-penetrating Radar
GRS	Gamma-ray Spectrometer
HiRISE	High Resolution Imaging Science Experiment
HST	Hubble Space Telescope
IACS	International Association of Cryospheric Sciences
IAG	International Association of Geomorphologists
ICE-SAG	Ice and Climate Evolution Science Analysis Group
ICMPSE	International Conference on Mars Polar Science and Exploration
ISRU	In Situ Resource Utilization
KISS	Keck Institute for Space Studies
LDA	Lobate Debris Apron
MARCI	Mars Color Imager
MARSIS	Mars Advanced Radar for Subsurface and Ionosphere
MAVEN	Mars Atmosphere and Volatile Evolution
MCID	Massive CO <sub>2</sub> Ice Deposit
MCS	Mars Climate Sounder
MEPAG	Mars Exploration Program Analysis Group
MGS	Mars Global Surveyor
microCT	Micro-computed Tomography
MOC	Mars Orbiter Camera
MOLA	Mars Orbiter Laser Altimeter
MORIE	Mars Orbiter for Resources, Ices, and Environments
MOSAIC	Mars Orbiters for Surface-Atmosphere-Ionosphere Connections
MRO	Mars Reconnaissance Orbiter
NASA	National Aeronautics and Space Administration (USA)
NEX-SAG	Next Orbiter Science Analysis Group
NIR	Near-infrared
OMEGA	Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité
PEDE	Planet-encircling Dust Events
PSTAR	Planetary Science and Technology from Analog Research
RIMFAX	Radar Imager for Mars's Subsurface Experiment
SAR	Synthetic Aperture Radar
SHARAD	Shallow Radar
SpaceX	Space Exploration Technologies Corp.
SWIM	Subsurface Water Ice Mapping (project)
TGO	Trace Gas Orbiter
UAS	Unoccupied Aircraft System
VFF	Viscous Flow Feature
WISDOM	Water Ice and Subsurface Deposit Observation on Mars
WRAP	Widespread Recent Accumulation Package

- 2nd ICMPSSE: Reykjavik, Iceland, 2000 August 21–25 (Clifford et al. 2001).
- 3rd ICMPSSE: Lake Louise, Alberta, Canada, 2003 October 13–17 (Clifford et al. 2005).
- 4th ICMPSSE: Davos, Switzerland, 2006 October 2–6 (Fishbaugh et al. 2008).
- 5th ICMPSSE: Fairbanks, Alaska, 2011 September 12–16 (Clifford et al. 2013).
- 6th ICMPSSE: Reykjavik, Iceland, 2016 September 5–9 (Smith et al. 2018).
- 7th ICMPSSE: Ushuaia, Argentina, 2020 January 12–18 (this paper).

A distinctive characteristic of the ICMPSSE is that each oral session concludes with a 30-minute discussion period, enabling attendees to further examine the topics presented and questions raised. As a result, key advances become clearer and open questions are raised that drive future investigations from a more unified perspective. Starting with the 6th ICMPSSE, a team of volunteer synthesizers assembles the most important points from the sessions and discussions during the conference, and a final plenary session gathers these syntheses to define the present major open questions in the field. In the previous (6th) edition, five major open questions were identified, each corresponding to a major theme of Mars Polar Science, and each with a set of subquestions, desired measurements, and proposed investigations for the future. The five top-level questions from the 6th ICMPSSE were:

Q1. Polar atmosphere: What are the dynamical and physical atmospheric processes at various spatial and temporal scales in the polar regions, and how do they contribute to the global cycle of volatiles and dust?

Q2. Perennial polar ices: What do the characteristics of Martian polar ice deposits reveal about their formation and evolution?

Q3. Polar record of past climate: How has the Martian climate evolved through geologic history, what are the absolute ages of the observable climate records, and how should we interpret the records of past states?

Q4. Nonpolar ice: What is the history and present state of the mid- and low-latitude volatile reservoirs?

Q5. Present-day surface activity: What are the roles of volatiles and dust in surface processes actively shaping the present polar regions of Mars?

These five questions served as the basis for the organization of the 7th ICMPSSE. Submitted abstracts were classified according to these five themes, and syntheses and discussions revolved around progress that has been made in each of the themes and how to redefine the questions based on new developments. In four years, many of the specific investigations encompassed by these questions and detailed in Smith et al. (2018) have been fully or partially addressed (see Section 2). Thus, this paper restructures and redefines the currently open questions in Mars Polar Science as agreed upon in discussions among the synthesizers and participants of the 7th conference. Furthermore, with the addition of a sixth top-level question, the paper also seeks to frame Martian cryospheric studies within the larger context of planetary science.

### 1.3. The 7th ICMPSSE: Expansion to South America

The 7th edition of the ICMPSSE was held on 2020 January 13–17, in the city of Ushuaia, province of Tierra del Fuego,

Argentina. Ushuaia was chosen for several reasons. As with past conferences, it was important for the conference site to be proximal to good field examples of glacial geomorphology and glaciology that could be viewed as an analog for a variety of Martian polar and cryospheric terrains. This is because a central feature of the ICMPSSE since its second edition is the organization of field excursions, with the goal of observing and learning about potential analogs to Martian glacial landscapes and discovering sites that could inspire fieldwork-based collaborations between Mars polar researchers and local scientists. Ushuaia sits on the shores of the Beagle channel, itself a massive glacial valley carved by the Beagle paleo-glacier. As such, the city is surrounded by glacial and post-glacial geomorphology that evolved during the Last Glacial Maximum (Rabassa et al. 2000 and references therein) and provided excellent opportunities for field excursions during the conference. In addition, a short flight north from Ushuaia leads to the southernmost region of Patagonia, in the province of Santa Cruz, where proximity to the southern Patagonian Ice Field and its active glaciers (such as the famous Perito Moreno glacier) allowed the organization of a 5-day post-conference field trip exclusively focused on past and present glacial processes. The field trips were led by expert Patagonian glaciologists and geomorphologists from CADIC/CONICET, who hosted the conference and participated in the sessions and discussions.

Among the main goals of the ICMPSSE is that of promoting the exchange of knowledge and ideas between planetary scientists and terrestrial geologists, glaciologists, and paleoclimatologists. Since the first edition of the conference, concerted efforts have been made by the organizers to reach out to earth scientists whose interests overlapped with Mars polar research, resulting in the growth of the community and the application of novel ideas from terrestrial research to the Martian system. In this spirit, the 7th edition looked to expand the community beyond North America and Europe, reaching out to the community of South-American terrestrial glaciologists and geomorphologists specializing in the geology and environment of Patagonia. The 7th ICMPSSE thus marked the first time that the conference visited the southern hemisphere. As a result, the conference received a great deal of attention from the local press, the organizers made lasting contacts with local glaciologists, and local early-career scientists and university students were inspired by the presence of a “Martian ice” conference in their city. Over 75 planetary and terrestrial scientists from all over the world, including the host nation and region, attended the conference. Nearly a third of attendants were PhD and Master’s students and half were early-career scientists.

The conference was organized into 12 oral sessions, an evening poster session, discussion periods, and a “synthesis and future plans” panel. As is usual in the ICMPSSE, special attention was also given within the conference itself to learning about the geomorphology of the area and its applicability as a Martian analog. For this purpose, a special presentation on the glacial landforms of Patagonia and Tierra del Fuego kicked off activities on Sunday, January 12. Before the regular sessions began on Monday, the participants reviewed the MEPAG Mars science goals document (MEPAG 2020) and mission concepts from MEPAG’s Ice and Climate Evolution Science Analysis Group (MEPAG ICE-SAG 2019). The research objectives and priorities identified by these groups are based on community

input to the ongoing U.S. Decadal Survey on Planetary Science and Astrobiology 2023–2032 process, which itself will feed into NASA’s selection of future missions and projects in planetary science over the next decade. The MEPAG and ICE-SAG results were presented before the topical sessions began so that discussions regarding specific research areas could be framed with the larger context in mind and result in organized community input for future discussions with organizations such as MEPAG or the Decadal Survey committee.

The regular sessions roughly correlated with the scientific themes of the 6th ICMPSSE but also included dedicated sessions for Earth-analog research and mission/instrument concepts that are being developed and/or have been recently proposed to space agencies. Each session included a set of about 10 presentations, after which ample time was allotted for community discussion. With white papers for the NASA Planetary Science Decadal Survey due in 2020 July, a main goal of this conference was to identify priorities for measurements and missions that could significantly advance Mars Polar Science in the next decade. Thirteen white papers related to Martian polar and/or climate science authored or coauthored by 7th ICMPSSE participants were submitted to the NASA decadal survey (Bapst et al. 2021; Becerra et al. 2021; Bramson et al. 2021; Brown et al. 2021; Dinięga et al. 2021a, 2021b; Dundas et al. 2020a; Grau Galofre et al. 2021; Horgan et al. 2021; Sarrazin et al. 2021; Smith et al. 2021b; Tamppari et al. 2021; Zurek et al. 2021), and one to the ESA Voyage 2050 planning process (Thomas et al. 2019, 2021). Most of these white papers referenced research and/or ideas that were discussed or presented at the 7th ICMPSSE, exemplifying the effectiveness of the conference in uniting the community toward common goals. The present paper summarizes the state of Mars Polar Science (as defined above) by gathering input from the 7th ICMPSSE synthesis notes, presentations, and submitted white papers.

## 2. Key Science Questions and Advances

The definition of advances since the last conference and the proposal of new or restructured open questions to guide the field over the next few years are major goals of the ICMPSSE. The research presented at the conference is evaluated in the context of the established open questions (Smith et al. 2018) so that the questions themselves can be redefined to reflect advancements. After the 6th edition of the conference, the major open questions in the field were entirely redefined and rewritten and were given more detail in the form of more specific subquestions and targeted investigations (Smith et al. 2018). In the years between the 6th and 7th conferences, these themes were used as the foundation for many independent studies, including a Keck Institute for Space Science workshop (Smith et al. 2020) that eventually developed into a NASA Discovery-class mission proposal (Byrne et al. 2020, 7ICMPSSE).

The questions below are the updated open questions agreed upon during the 7th ICMPSSE. The subsections for each theme contain several desired investigations that contribute to answering various parts of the corresponding top-level question. Within the text relevant to each theme, we briefly describe the overall motivation for the question and the contributions to that theme that were presented at the conference, which directly contributed to the reworking of the desired investigations to their current form. The presented advances rarely contribute to only one of the top-level questions; they usually address many cross cutting themes (Smith et al. 2018) and are in this way all connected to open

questions about the entire Martian cryosphere. This will be evident throughout the text below and highlighted for the most interdisciplinary cases.

Mars Polar Science is by nature interdisciplinary, and one of our goals as a community is to continue to expand collaborations with many fields of science that can contribute knowledge applicable to the field. In this context, we reiterate that the scope of the ICMPSSE includes not just the polar regions of Mars but its entire cryosphere (i.e., the solid-state volatile components of the planet) and its interaction with the climate. From a geochronological viewpoint, the scope covers mostly the timescales during which the currently existing cryosphere has interacted with the environment (thus preserving a record of these interactions), i.e., the Late Amazonian period (the past several hundred million years). However, several relevant studies are concerned with Mars’s ancient cryosphere and investigate the geologic footprint left behind by processes such as glaciations from the Late Noachian/Early Hesperian (3–4 Ga) periods (e.g., Grau-Galofre et al. 2020). In total, there were 77 contributions submitted to the conference: 63 in the form of oral presentations, 10 posters, and 4 as print only.

*Question 1, Polar atmosphere: What atmospheric processes take place currently at various spatial and temporal scales in the polar regions, and how do they contribute to the global cycle of volatiles and dust?*

- (a) Quantify the interplay of current local, regional, and global circulations in the polar regions—including but not limited to the polar vortex, katabatic winds, and transient eddies—from the surface throughout the atmosphere.
- (b) Characterize the current and past transport of volatiles and dust aerosols into and out of the polar regions, including interannual variability, and through obliquity variations.
- (c) Understand and predict the condensation of water and CO<sub>2</sub> ice clouds and their impact on the thermal structure and atmospheric circulation.
- (d) Determine present-day dust deposition patterns over the polar caps and the specific mechanisms enabling dust lifting in polar regions.

It is impossible to understand the history and evolution of any planet’s climate and environment—a central objective of planetary science—without knowledge of its current climatic state. On Mars, the history, present existence, and survival of volatile ices are inextricably linked to the atmosphere through surface–atmosphere interactions. Therefore, in a general sense, this question motivates investigations focused on understanding the current atmospheric and climatic state of the planet in the context of its interaction with the Martian cryosphere.

The current Martian climate allows for a substantial exchange of energy, volatiles, and dust between the poles of Mars and lower latitudes. The atmosphere is 95% CO<sub>2</sub>, up to a quarter of which condenses onto each pole every winter to form seasonal caps of CO<sub>2</sub> ice that give rise to some of the most dynamic processes in the solar system (see Question 5). Mars also is subject to frequent regional dust storms and even planet-encircling dust events (PEDEs), which can cover the entire planetary surface and result in significant redistribution of dust.

Research presented at the 7th ICMPSSE focused on comparing the north and south polar atmospheres and their interactions with

the surface. Like most areas of Mars research, atmospheric studies have benefited heavily from the decades-long orbital monitoring of the planet. Aye & Hayne (2020, 7ICMPSE) took advantage of the multiyear opacity data from the MCS to contrast the development of the north and south polar vortices. As is the case on other planets, the Martian atmosphere develops strong circumpolar zonal winds on its winter pole—polar vortices—that limit the mixing of air in the poles and midlatitudes and thus affect seasonal CO<sub>2</sub> condensation and dust and aerosol transport onto the polar regions (Seviour et al. 2017). The polar vortices influence the transport of water vapor in and out of the polar region. Greybush et al. (2019a, 2019b) used data assimilation—a relatively recent advance in Mars atmospheric science that is proving highly valuable—to show that transport occurs near 50 Pa (~25 km) and near 550 Pa (boundary layer). The study also revealed disturbances in the polar vortex boundaries that may be responsible for north–south differences in transport. Temperature profiles at the vortices’ cores, retrieved from the recently released 2D MCS retrieval data set that performs better in the polar regions (Kleinböhl et al. 2017), revealed that south polar atmospheric temperatures drop by up to 5 K below the CO<sub>2</sub> frost point (Kleinböhl et al. 2020, 7ICMPSE). This is in contrast to the north polar atmosphere—which only drops ~1–2 K below the CO<sub>2</sub> frost point—and thus implies a local CO<sub>2</sub> depletion in the north that corresponds to an enhancement of noncondensable gases by up to a factor of 7 (Piqueux et al. 2020, 7ICMPSE). The energy balance in the polar regions and how and why it differs between poles need to be better understood.

The extent to which the polar atmosphere is well mixed was also discussed. This is relevant to transport, as well as to surface–atmosphere exchange and to the possible buffering of subsurface ice or the likelihood of deliquescence in the case of a salty regolith. Piqueux et al. (2020, 7ICMPSE) suggested that the south polar atmospheric column is well mixed, consistent with global circulation models, and that the resulting transport in and out of the polar vortex is small. However, in the north polar region, he found that the atmospheric column is poorly mixed, perhaps only up to 2–3 km, but possibly much less. This may point to an unidentified dynamic process that acts to limit mixing and is consistent with recent results from Tamppari & Lemmon (2020) that showed an enhanced water layer in the lowest ~2.5 km at the Phoenix location. These differences reveal the need to understand in more depth and detail the atmospheric processes that affect the polar region and how they differ in the north versus the south, including transport, mixing, waves, dust events, and surface interactions.

Another result that was published shortly prior to the conference was the TGO observation of very high super saturation in the polar winter (Fedorova et al. 2020). They found super saturations of 5–10× in the polar region, near the surface, even in the presence of clouds. This is a surprising result and is actively being investigated. Again, this result further suggests a current lack of understanding of how the Martian atmosphere can achieve such high super saturations and what this could mean for deposition and transport.

MCS monitoring of Mars also allowed detailed, global observations of the onset, development, decay, and effects of a PEDE that took place between 2018 May and October (Guzewich et al. 2020). PEDEs are the rarest and largest dust storms on Mars, with only 11 events known to have occurred since 1950. MCS continuously tracked the 2018 PEDE and established that these events develop and grow much faster

than even the largest regional dust storms (Kass et al. 2020). The impact of the 2018 PEDE on atmospheric dynamics at both poles was considerable. The most notable effect was to significantly weaken the high-altitude westerly zonal jet, heating the southern hemisphere through dust loading and diminishing the high-to-low-latitude temperature contrast that drives the polar westerly zonal jet (Streeter et al. 2020, 7ICMPSE).

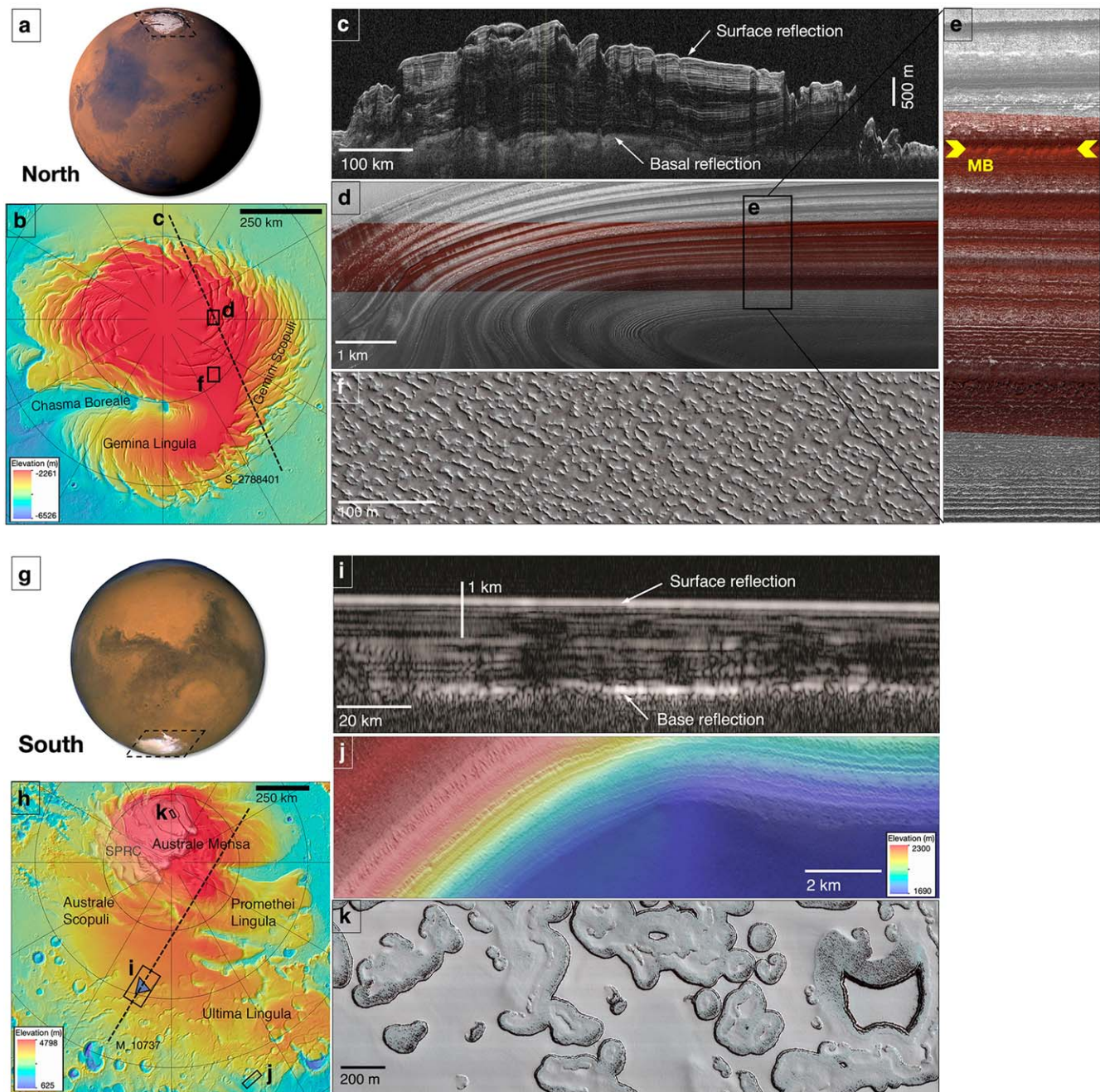
Multiyear analysis with data from the MAVEN spacecraft (Jakosky et al. 2015) was also possible for the first time. MAVEN had only completed its first year of operations in 2016, so these studies were not yet possible at the time of the 6th ICMPSE. A 5 yr (2.5 Mars year) MAVEN data set uncovered the role of the polar regions in the energy input from the solar wind into the lower atmosphere (Andersson & Pillinski 2020, 7ICMPSE). The lack of an intrinsic dipole magnetic field at Mars means that the polar atmosphere/ionosphere (1) does not channel much energy into the thermosphere and (2) has weaker diurnal variations than the equatorial atmosphere. This leads to a high heavy-ion escape at Mars compared to Earth.

*Question 2, Perennial polar ices: What do the characteristics of Martian polar ice deposits reveal about their formation and evolution?*

- (a) Determine the energy and mass balances (e.g., amount of water, CO<sub>2</sub>, and dust/aerosols exchange) of the polar ice reservoirs and the temporal and spatial variations in processes that affect the energy and mass exchanges (precipitation, deposition, sublimation, erosion).
- (b) Characterize the properties of the polar residual caps (i.e., current distribution of ice, variety, composition, and evolution of topographical properties) and their relationship with seasonal and annual processes.
- (c) Characterize the compositional, chemical, and physical properties (both vertically and horizontally) of the materials in the PLDs and their BUs.
- (d) Constrain the amount of sediment (dust or sand) currently trapped within or below the PLDs and quantify their role and efficiency as agents that promote the preservation of buried volatile reservoirs.
- (e) Identify and quantify the morphological and compositional differences and similarities between the water-ice units of the north and south polar caps.
- (f) Test hypotheses regarding the presence of liquid water at the base of the polar caps at present or in the past.

In order to improve our understanding of the origin and evolution of the cryosphere of Mars, it is necessary to characterize the ices that compose it as completely as possible, starting with the permanent polar ices. Like Earth, Mars has kilometers-thick polar ice sheets over each pole (Figure 1). These ice caps have different icy units that interact with, and thus record, the climatic state at different timescales (Byrne 2009). The perennial ices are defined as those deposits that exist for longer than one Martian year, in contrast to the seasonal polar caps of carbon dioxide ice, which exist only during each respective winter, and are addressed in Question 5. Mars’s permanent ice caps have a combined volume approximately equal to that of the Greenland ice sheet on Earth, and each can roughly be divided into two units: the PLDs and the PRCs.

The PRCs lie on top of the PLDs in both poles, and each is very distinct from the other. The NPRC is made entirely of



**Figure 1.** The Martian poles at a glance. (a) HST image of Mars with the bright NPRC in view. (b) Topographic map of the NPLD (MOLA; Smith et al. 2001) with major geographic features indicated. (c) Vertically exaggerated SHARAD radargram (ID: 3263101) of the NPLD (dashed line in panel (b) shows the radar orbit track). Arrows indicate the surface and base reflectors of the NPLD. (d) HiRISE image of an outcrop in an NPLD trough (ID: PSP\_001738\_2670). (e) Zoomed-in view of the area outlined in panel (d). Yellow chevrons point to a typical Marker Bed. (f) HiRISE image of the typical surface texture of the NPRC (ID: ESP\_027085\_2630). (g) HST image of Mars with the SPRC and south seasonal ice in view. (h) Topographic map with geographic features of the SPLD. The areal extent of the SPRC is indicated. (i) MARSIS radargram of the region of the SPLD indicated in panel (h). The bright basal reflection has been interpreted to be liquid water  $\sim 1.5$  km below the surface. The geographical extent of the detection of this basal reflection is indicated by the blue triangle in panel (e) (MARSIS orbit: 10737, adapted from Figure 2 of Orosei et al. 2018). (j) CaSSIS DTM of a marginal outcrop in Ultima Lingula (stereo pair IDs: MY34\_002154\_266\_1 and \_2). (k) Typical appearance of the “swiss cheese terrain” of the SPRC (HiRISE ID: ESP\_040328\_0940).

highly reflective, very sparsely cratered water ice. It is currently assumed to be the most recent PLD stratum and thought to be accumulating today (Landis et al. 2016). Continuous analysis of ultra-high-resolution images from HiRISE (McEwen et al. 2007) on board NASA’s MRO shows evidence for many types of ongoing activity in the north polar region, consistent with this picture of a young NPRC surface (Herkenhoff et al. 2020, 7ICMPSE). The wavy structure of crests and troughs of the

NPRC has a wavelength of  $\sim 10$  m (Byrne 2009) and is relatively uniform throughout its surface, which covers most of the NPLD (Figures 1(a), (f)). The SPRC, however, is almost entirely carbon dioxide ice and covers only a small portion of the SPLD surface (Figure 1(g)). It appears to often be replenished during winter by accumulation of seasonal  $\text{CO}_2$  (Byrne et al. 2003; Thomas et al. 2013, 2016; Becerra et al. 2015; Buhler et al. 2017). The  $\text{CO}_2$  ice gives it an extremely

bright surface, which is heavily eroded by circular pits and linear troughs—often referred to as “swiss cheese” (Figure 1(k)) and “fingerprint” terrain, respectively—that result from differential sublimation of the CO<sub>2</sub> ice (Byrne & Ingersoll 2003). The discovery (Phillips et al. 2011) and subsequent characterization of larger subsurface reservoirs of CO<sub>2</sub> ice beneath the SPRC that are bounded by thin layers of water ice (Bierson et al. 2016) have led to the hypothesis that the SPRC arises from mass and energy balance equilibration as subsurface CO<sub>2</sub> ice sublimates into the atmosphere during the present epoch of Mars’s increasing obliquity (Buhler et al. 2020a; see also Question 3).

The morphological and thermophysical characteristics of the residual caps can lead to estimates of age or help discern whether accumulation can currently take place. For instance, thermophysical analyses support near-surface (<1 m) layering in the NPRC in the form of a sharp decrease in porosity with depth, which supports recent accumulation (Bapst et al. 2019). Wilcoski & Hayne (2020) found that the roughness of the NPRC can be indicative of its surface age and estimated that the 10 m periodic roughness of the surface took between 1 and 10 kyr to form. In the south, data-derived thermophysical properties of water-ice exposures at the edges of the SPRC were also shown to correlate with the presence of porous ice (Bapst & Piqueux 2020, 7ICMPSE), implying recent accumulation and supporting a prior hypothesis (Montmessin et al. 2007). The evolution of the SPRC is also evident in spectrometry data from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM; Murchie et al. 2007), which show a clear variation in water and CO<sub>2</sub> ice properties intra- and interannually (Cartwright et al. 2020, 7ICMPSE) and reveal an increase in dust content on the edges of swiss cheese pits as they grow (Campbell et al. 2020, 7ICMPSE).

The PLDs constitute the vast majority of the polar ice and are made primarily of water ice arranged in layers or strata (Figures 1(c), (d), (i), (j)) that have been observed since the times of Mariner 9 (Cutts 1973). This stratification is most likely due to differing amounts of entrained silicate dust carried by Martian winds and dust storms (Byrne 2009). At large scales, both PLDs are similar in many ways, but they also have important differences. The NPLDs are about 2 km thick and are made of 95% pure water ice, on average (Grima et al. 2009), while the SPLDs have a thickness of almost 4 km and a higher average dust content of up to 15% (Plaut et al. 2007; Zuber et al. 2007). Direct imaging of the PLD strata is possible owing to the presence of extensive spiral troughs (Cutts et al. 1979; Smith & Holt 2010) that dissect the ice sheets and expose the bedding (Figures 1(b), (h)). At radar wavelengths, however, it is possible to “see through” the PLD ice. Since water ice has a relatively low dielectric permittivity, the radar signal experiences little attenuation, but part of it is reflected upon contact with subsurface layers with varying amounts of dust. This allowed the MARSIS (Picardi et al. 2005) and SHARAD (Seu et al. 2007) radars to view the internal structure of both PLDs (as seen, e.g., in Figures 1(c) and (i)), which confirmed the geographical uniformity of the layers (Plaut et al. 2007; Phillips et al. 2008) and permitted mapping of different geologic units and features within the PLD (Milkovich et al. 2009; Putzig et al. 2009; Holt et al. 2010; Smith et al. 2013; Whitten & Campbell et al. 2018). Recently, a new 3D SHARAD data set has been developed that reconstructs the volumetric structure of the PLD, essentially eliminating radar clutter (Holt et al. 2006) and providing a complete picture of the PLD interiors (Foss et al. 2017;

Putzig et al. 2018). This data set is already contributing to major discoveries (e.g., Putzig et al. 2018 observed impact craters preserved within the ice sheets).

Most research to date has focused on studying the ice in the PLD; however, characterizing the dust component is vital to retrieving the climate record (Yoldi et al. 2020, 7ICMPSE). Sixteen years of continuous monitoring with the OMEGA spectrometer of ESA’s Mars Express revealed important differences between the dust loading of the NPRC after the 2005 PEDE and that after the 2018 PEDE (Langevin & Gondet 2020, 7ICMPSE; Gondet et al. 2020, 7ICMPSE). This is reflected in the lithic components observed in the PLD troughs. Sinha & Horgan (2020, 7ICMPSE) used CRISM spectral cubes to characterize the composition of these lithics. They found that although both PLDs are spectrally dominated by ferric dust, there are clear mafic signatures (particularly at the base of marginal scarps) in and around the PLDs. The presence of mafic materials means that these sediments are datable, so the absolute age of the PLD could potentially be constrained through radiometric age dating by a future landed polar mission.

In terms of the properties of the ice sheets and PLD layers themselves, recent advances in data analysis have resulted in important constraints on the physical characteristics of the various stratigraphic units (Holt 2020, 7ICMPSE). Topographic, radar, and gravity data were combined to derive the density of the NPLD ( $1126 \pm 38 \text{ kg m}^{-3}$ ) and its underlying, sandier BU ( $2007_{-445}^{+493} \text{ kg m}^{-3}$ ; Ojha et al. 2019, 2020, 7ICMPSE). These values for the BU density indicate water-ice contents in the BU of  $55\% \pm 25\%$ , which was confirmed by SHARAD observations that found the permittivity of the BU to be consistent with 62%–88% water ice (Nerozzi & Holt 2019; Nerozzi et al. 2020, 7ICMPSE). Directly above the BU, the lowermost 500 m of the NPLD were mapped in detail with SHARAD and observed to have significant stratigraphic complexity in the form of “pinch-out” unconformities and thickness variations (Nerozzi & Holt 2017).

Characterization of the upper units of the NPLD, which hold the most easily observable record, is also making steady advances. Though changes in the reflectivity of subsurface radar signals could constrain dust content in the icy NPLD layers (Lalich et al. 2019), it is difficult to discern when these differences are caused by one thick layer or multiple thinner layers (Lalich et al. 2020, 7ICMPSE). So-called Marker Beds—dark, thick exposed layers in the NPLD—have been assumed to correlate to radar subsurface layer reflections (also called “reflectors”), but a one-to-one correlation has yet to be made (Christian et al. 2013). High-resolution imaging and topography of Marker Beds exposed in troughs has, by itself, already been used to map the upper NPLD stratigraphy across hundreds of kilometers (Fishbaugh & Hvidberg 2006; Becerra et al. 2016). However, an obstacle to determining the uniformity of the record exposed is the variability in thickness and morphology of a Marker Bed along the strike of a single trough, which highlights the importance of achieving a radar-to-visible correlation (Becerra et al. 2020b, 7ICMPSE). This morphological variability suggests that dust retention and/or ice sublimation along a trough is heterogeneous (Pascuzzo et al. 2020, 7ICMPSE), consistent with the finding that a dust veneer on the order of millimeters can shut down sublimation within a trough (Bramson et al. 2019; Pascuzzo et al. 2021).

Before the 6th ICMPSSE, the SPLD was significantly understudied compared to the NPLD. However, this has changed in the past 5 yr. SHARAD and MARSIS data have been used to map the SPLD stratigraphy throughout its geographical extent (Whitten et al. 2017, Whitten & Campbell 2018) and to characterize the basal interface of the SPLD in detail (Abu Hashmeh et al. 2020, 7ICMPSE; Plaut 2020, 7ICMPSE). Details of the surface properties of the SPLD are also being inferred through the study of recently formed, dated impact craters (Landis et al. 7ICMPSE), which may reduce the uncertainty in the surface age of the SPLD.

One of the most salient discoveries in Mars Science in the past 4 yr came from observations of anomalously bright MARSIS radar reflections in the SPLD, which have been interpreted to be caused by localized liquid water at the SPLD base (Figures 1(h), (i); Orosei et al. 2018; Lauro et al. 2021). However, recent radar propagation models show that subsurface beds of solid CO<sub>2</sub> and water (materials already known to exist in the SPLD) could constructively interfere to form similarly bright reflections (Lalich et al. 2021). If liquid water is present, this could reshape many aspects of Mars science, as the presence of melt at the base of the SPLD would require not only a high concentration of salts to lower the melting point of water (Hecht et al. 2009; Fisher et al. 2010; Hanley et al. 2020, 7ICMPSE) but also a pronounced enhancement in the local heat flux, such as what could be achieved by a near-surface magma chamber emplaced within the past ~100 s kyr (Sori & Bramson 2019). It is imperative that what could be a landmark discovery in Mars science be followed up with intense research scrutiny, much like the enigmatic Recurring Slope Lineae (McEwen et al. 2011, 2021) of the Martian equatorial latitudes.

*Question 3, Polar record of past climate: How has the Martian climate evolved through time, what are the absolute ages of the observable climate records, and how can we interpret these records to know what climatic states they represent?*

- (a) Determine and characterize the link between astronomically forced climate parameters and resultant layer properties of the PLD and off-polar deposits.
- (b) Characterize unconformities to determine time spans that are not recorded in the PLD and estimate the volume/mass of the missing material.
- (c) Further test the current hypothesis that NPLD formation began at ~4 Ma.
- (d) Estimate the climatic conditions that could have formed and preserved the SPLD, constrain its surface age, and identify major SPLD water-ice units to determine whether they were deposited in one or multiple periods of favorable climate.
- (e) Characterize the processes that drive the formation and evolution of the buried CO<sub>2</sub> ice reservoirs at the south pole and determine when these processes operated.
- (f) Determine how the SPLD relates to the much larger DAF in terms of climate epochs that are recorded, and the similarity between the climates that produced the SPLD and the DAF.

The stratified structures of the PLD have long been believed to be the product of shifts in climate that periodically change the amount of volatiles and dust transported to and from the polar surfaces (Cutts 1973; Murray et al. 1973; Toon et al. 1980; Cutts & Lewis 1982; Howard et al. 1982; Laskar et al. 2002). These shifts are themselves a consequence of oscillations in

Mars's astronomical parameters (Laskar et al. 2004), just as climate cycles on Earth depend on Milankovitch cycles (Hays et al. 1976; Hinnov 2013). As a consequence, a central driving goal of Mars Polar Science is that of accurately interpreting the connection between the PLD and Mars's astronomically forced climate change, namely, "reading" the polar climate record and its chronology<sup>20</sup> (Smith et al. 2018, 2020).

Remote-sensing images and radar data combined with models of orbitally forced climate evolution have contributed to our current interpretation of the PLD records. In the NPLD, periodicities in the change in brightness with depth of layer outcrops (Figure 1(e)) were theorized to be connected to orbital cycles (Laskar et al. 2002; Milkovich & Head 2005; Perron & Huybers 2009). Similar periodicities were also later observed in the high-resolution topographic signature of Marker Beds and of sets of thinner, also highly protruding layers (Fishbaugh et al. 2010a, 2010b). A periodic nature was also evident in the radar, with SHARAD observing a structure consisting of up to five packets of finely spaced reflectors separated by interpacket regions of low reflection (Figure 1(c); Phillips et al. 2008), which were understood to be connected to periods of low insolation and high ice deposition (Putzig et al. 2009). Models of paleoclimate used the orbital evolution of Mars to simulate the buildup of icy layers in the NPLD (Levrard et al. 2007) and, in general, were able to reproduce several aspects of the observed periodicities (Hvidberg et al. 2012). Importantly, models agree that the onset of the NPLD is likely to have occurred around 4 Ma, because the higher mean obliquity of Mars before that time would not have allowed surface ice to accumulate at the polar regions. The most recent time-series analyses of the stratigraphy of the NPLD (Becerra et al. 2017) detected ratios in stratigraphic wavelengths defined by layer protrusion that match the ratio between the oscillation frequencies of obliquity (120 kyr) and argument of perihelion (51 kyr). When coupled with an assumption that the surface is very young (Landis et al. 2016) or currently accumulating, these observations agree with the modeled age limits for the NPLD. Furthermore, the prediction by Levrard et al. (2007) that a discontinuity would be visible in the geologic record around 300 m, corresponding to a climate shift at ~400 Ka, was observed by SHARAD in the form of the WRAP unconformity (Smith et al. 2016; Whitten & Campbell 2018).

As was the case in Question 2, the older age and more complex nature of the SPLD have limited research on its climate record in the past, but this has also begun to change in the past 5 yr. An obvious obstacle for the general applicability of current models to the SPLD comes from its surface age, which is estimated to be at least 10 Ma (Herkenhoff & Plaut 2007; Koutnik et al. 2002), meaning that the onset of the SPLD would be much older than the obliquity shift at ~4 Ma and far enough in the past that models for astronomical parameters are not uniquely determined. Levrard et al. (2007) attempted to explain this paradigm by assuming that water-ice sublimation could limit itself by leaving behind thick dust lags that would slow sublimation, but they found that the polar ice still did not survive prior to 4 Ma in the model. However, their

<sup>20</sup> This is slightly different from what would be considered "reading" a climate record on Earth, where ice and sediment cores allow a complete knowledge of the properties of past climates. On Mars, current data allow us to associate geological deposits with orbital oscillations and make inferences about past climatic states. As the field and technology progress, the prospect of retrieving a Martian ice core with robotic or crewed missions may not be out of the question and would allow a true "reading" of the record.



model assumed that sublimation continued with dust lags of up to 1 m, and a recent phenomenological model for the migration of spiral troughs in the NPLD indicated that as little as a few millimeters of dust lag may be enough to significantly reduce sublimation rates (Bramson et al. 2019). Though the predictions of this model still agree that spiral troughs must be younger than 4 Ma, the stronger reduction in sublimation rates that was plausibly simulated, coupled with new crater production functions that suggest younger SPLD ages (Landis et al. 2020, 7ICMPSE), motivates future research to decipher the SPLD climate record.

In terms of evidence of climate forcing, Becerra et al. (2019) detected a similar ratio of stratigraphic periodicities in SPLD layer outcrops to that observed in the NPLD, suggesting similar forcing frequencies in both PLDs. The measured stratigraphic wavelengths in the SPLD suggested that at least three different units were deposited with different accumulation rates, in accordance with the different units that had been mapped by Milkovich & Plaut (2008). In addition, a new radar processing technique was used with SHARAD data to discover that the depositional center of the SPLD has oscillated, in both extent and location (Whitten et al. 2017), and to demonstrate the lateral continuity of SPLD layers through its entire areal extent (Whitten et al. & Campbell 2018).

Specific to the SPLD, an additional record of climate exists in the Australe Mensa region informally known as the Massive CO<sub>2</sub> Ice Deposit (MCID; Phillips et al. 2011; Bierson et al. 2016). This unit has been the focus of extensive research in both radar observations and climatic modeling in the past 5 yr, starting with the discovery of multiple CO<sub>2</sub> ice units in the subsurface that are separated by water-ice layers (Bierson et al. 2016). Several models have converged on an MCID age of ~500 kyr (Bierson et al. 2016; Manning et al. 2019; Buhler et al. 2020a). Further, the Buhler et al. (2020a) model quantitatively produces an MCID stratigraphy similar to that observed (Bierson et al. 2016; Putzig et al. 2018) and provides a mechanism for maintaining an SPRC in mass balance equilibrium that also agrees with observations (Thomas et al. 2016). Buhler & Piqueux (2021) and Buher et al. (2020b, 7ICMPSE) extended this model and used the MCID stratigraphy to constrain the exchangeable CO<sub>2</sub> inventory (including CO<sub>2</sub> adsorbed in the regolith) at obliquity timescales (~10<sup>5</sup> yr) to be 100<sup>+80</sup><sub>-34</sub> mbar equivalent (~17 times the mass of the present atmosphere). Additionally, relating the current vapor-equilibrium processes that regulate Mars's CO<sub>2</sub> deposits (Leighton & Murray 1966) to the secular drawdown of CO<sub>2</sub> (Kahn 1985) is a promising avenue for elucidating Mars's climatic evolution from the Noachian to the present day (Paige 2020, 7ICMPSE).

Finally, several recent investigations have focused on evaluating the connection of the polar climate records to other, nonpolar records, such as that of the DAF, which has been interpreted as the remnant of a Hesperian-aged ice cap (Plaut et al. 1988; Tanaka & Kolb 2001). In-depth analyses of both MARSIS and SHARAD radar data by Whitten et al. (2020, 7ICMPSE) have shown that the DAF is composed predominantly of dry sediments or basalt. Thus, any volatiles associated with the original incarnation of such an ice cap have been removed, so there is currently little evidence for preserved ancient ice here. Though it is possibly the most ancient record in this region, the DAF is not the only circumpolar record of climate that may be different from the PLD. Conway et al. (2012) showed that ice mounds in craters surrounding the

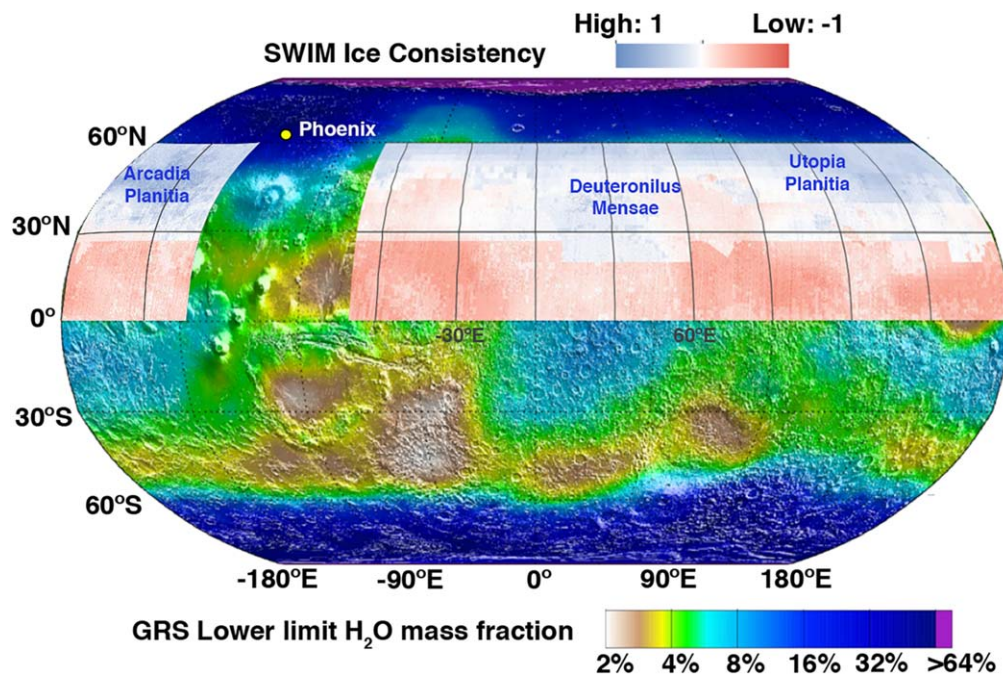
north polar region were likely formed independently from the NPLD through microclimate deposition. More recently, Sori et al. (2019) classified numerous, similar “islands of ice” in craters surrounding the south polar region, up to latitudes as far north as 64°S. These crater mounds likely contain their own record of climate, one that has yet to be investigated and interpreted.

*Question 4, Nonpolar ice: What is the history, present state, and relevance for astrobiology and human exploration of the mid- and low-latitude ice reservoirs on, just below, and deep below the surface?*

- (a) Inventory and characterize the nonpolar ices/volatile reservoirs at the surface and near-surface (locations, quantities, composition).
- (b) Determine the accessibility of water-ice deposits as a resource for future human exploration, in particular the lowest latitudes under which water-ice reservoirs can be found and their properties (e.g., depth to the top of the ice, scales of vertical and lateral heterogeneities, quantities of impurities).
- (c) Determine the conditions under which the nonpolar volatile reservoirs accumulate and persist.
- (d) Interpret the climate record present in nonpolar ice deposits.
- (e) Determine how chemical differences (i.e., presence of salts) influence the movement of volatiles and their impact on habitability.
- (f) Investigate whether liquid water exists or has existed in locations associated with mid- and lower-latitude ice deposits. Could these have provided habitats for, or preserved evidence of, past or present life?

The widespread presence of near-surface water ice across the midlatitudes (~30°–60°) of Mars has major implications for the planet's climate history, total water budget, and, consequently, the possibility of past life and the potential for human exploration. Midlatitude ice has been of particular interest in the Mars science community because (1) its existence in the present day implies a past change in orbitally forced climate (Head et al. 2003), (2) it suggests the preservation of ice deposits over millions of years or longer (Bramson et al. 2017), and (3) it is easily accessible for ISRU by human missions (Golombek et al. 2003).

The present-day existence of a so-called “latitude-dependent water-ice-rich mantle” (Kreslavsky & Head 2002) was initially inferred through altimetry measurements by the MOLA (Zuber et al. 1992) and images by the MOC (Malin & Edgett 2001). The concurrent discovery of substantial amounts of water-ice-equivalent hydrogen in the midlatitudes by the GRS on Mars 2001 Odyssey provided robust signs of subsurface ice (Figure 2; Boynton et al. 2002). Following the arrival of MRO at Mars, CTX and HiRISE provided direct evidence of the presence of this ice in images of recent impact craters (Byrne et al. 2009), and the higher resolution permitted detailed mapping of ice-related geomorphic “viscous flow features” (VFFs), such as CCFs (Levy et al. 2010), glacier-like forms (GLFs; Hubbard et al. 2011), Lobate debris aprons (LDAs; Levy et al. 2014), and expanded craters (Viola et al. 2015). Furthermore, the Phoenix lander directly probed Martian subsurface ice in situ when it found excess and pore-filling ice in 8 of the 12 trenches it dug (Mellon et al. 2009; for the definitions of “excess,” “pore” or “pore-filling,” and “massive” ice used here, see Harris et al. 1988). Perhaps most importantly, SHARAD detected abundant subsurface radar reflections



**Figure 2.** Maps of subsurface ice presence in the midlatitudes. The background map shows the lower limit water mass fraction estimates from GRS data (Boynton et al. 2007) over MOLA shaded relief topography. Superposed between 0° and 60°N latitude is the map of shallow subsurface ice consistency for the SWIM project study area (Morgan et al. 2021). This parameter combines data from neutron spectroscopy, thermal signatures, surface geomorphology, and radar surface and subsurface echoes. Bluer areas correspond to a higher consistency with shallow ice, while redder areas are consistent with the absence of ice. Also indicated are Arcadia and Utopia Planitiae, Deuteronilus Mensae (where several studies have interpreted the existence of large subsurface ice sheets), and the Phoenix landing site (yellow oval).

attributed to midlatitude ice in various forms, including buried glaciers (Holt et al. 2008), LDAs (Plaut et al. 2009), and vast subsurface ice sheets beneath major regions such as Arcadia (Bramson et al. 2015) and Utopia (Stuurman et al. 2016) Planitiae (Figure 2).

Since the 6th ICMPSSE, several efforts have focused on constraining the distribution of midlatitude ice on Mars to improve our understanding of the current stability of this ice and the global water budget. A series of studies performed global and regional mapping of ice-related landforms at three sites across the northern plains (Orgel et al. 2019; Ramsdale et al. 2019; Séjourné et al. 2019) and across the entire planet (Brough et al. 2018), the latter estimating that GLFs contain between  $\sim 500$  and  $1500 \text{ km}^3$  of ice ( $\sim 3\text{--}10 \text{ mm}$  water GEL). Research into regional geomorphology also continues to reveal signs of ice-related landforms in visible-NIR imagery (e.g., Viola & McEwen 2018) and radar (e.g., Petersen et al. 2018).

An essential unknown is the current distribution of pore ice and massive ice, particularly between 1 and 15 m in depth. SHARAD measurements are unable to resolve the upper  $\sim 5\text{--}15 \text{ m}$  of the subsurface, and GRS cannot resolve deeper than 1 m. Knowing this distribution is extremely important when estimating ice volumes and assessing resource accessibility (Abbud-Madrid et al. 2016).

In part to address this issue, and due to the growing interest for Martian ice as a resource, the SWIM project (<https://swim.psi.edu>) was organized from 2018 to 2020 with the express objective of integrating all orbital data sets (i.e., thermal, radar, neutron, visible) relevant to the characterization of subsurface ice (especially in the shallow subsurface) across the mid- and low latitudes (Bramson et al. 2020, 7ICMPSE; Morgan et al. 2021). The SWIM project has made substantial progress in mapping the distribution of nonpolar water ice across Mars,

refining prior assessments and significantly improving the spatial coverage. Results for the northern hemisphere (Figure 2) suggest that the shallow subsurface of Arcadia Planitia and the extensive glacial networks in Deuteronilus Mensae (Figure 2) have the most lines of evidence for widespread massive ice (Morgan et al. 2021).

Arcadia Planitia is one of the best-studied locations with confirmed shallow ice deposits. For example, Hibbard et al. (2021) used multiple orbital data sets to create a detailed map identifying locations where thick units of ice reside, and small-scale surface morphologies, such as polygonal and crenulated “brain” terrain (Hibbard et al. 2020, 7ICMPSE), have contributed to assessing stability (Williams et al. 2017). Elsewhere, visible and NIR data revealed excess, possibly massive, water ice exposed by fresh impact craters and erosional scarps at several midlatitude locations (Dundas et al. 2018, 2021a), in both the northern—consistent with the SWIM findings—and southern hemispheres (Figure 2). The ice exposed at erosional scarps is typically  $\sim 100 \text{ m}$  thick, comes to within  $\sim 1\text{--}2 \text{ m}$  of the surface, and appears stratified, hinting that it could also contain a potentially decipherable record of climate. In parallel, the ice exposed by recent impacts (Byrne et al. 2009; Dundas et al. 2014, 2021b) and by analysis of thermal (Piqueux et al. 2019) and neutron (Pathare et al. 2018) data sets (sensitive to the upper meter) concurs with the conclusion that this ice is within 1 m of the surface at many locations.

A rarely used data set in the midlatitudes that has the potential to impact the identification and characterization of nonpolar ice is gravity data. Gravity is sensitive to ice masses and has successfully been used to quantify polar ice on Mars (Zuber et al. 2007; Wieczorek 2008; Ojha et al. 2019). Yet, it has not been utilized to locate and quantify near-surface water ice in the midlatitudes. Sori et al. (2020, 7ICMPSE) used the most recently published static gravity field of Mars, GMM-3

(Genova et al. 2016), in an attempt to corroborate the radar data of buried ice sheets in Arcadia and Utopia Planitiae, and found only that such sheets had to be <330 m thick. However, the ice sheets are too small to resolve with the gravity data currently available, thus demonstrating the potential value of improved gravity data for Mars.

In addition to the obvious benefits of this research for future human explorers, the extensive midlatitude ice deposits and their associated landforms have important climate science implications, in that they hold additional records of climate during relatively recent periods of high obliquity (Viola 2020, 7ICMPSE; El-Maarry & Diot 2020, 7ICMPSE) since midlatitude and polar ice deposition likely takes place at different parts of the obliquity cycle. Further, recent studies used crater-dating and the superposition between various GLFs to estimate times for the onset (~300 Ma) and cessation (~2 Ma) of glaciations in midlatitudinal regions (Hepburn et al. 2020; Soare et al. 2021).

*Question 5, Present-day surface activity: What are the roles of volatiles and dust in surface processes actively shaping the present-day polar regions of Mars today, and what do they tell us about the long-term state and evolution of the polar caps?*

- (a) Determine the processes by which seasonal CO<sub>2</sub> (alone, or in conjunction with other surface materials) acts as an agent of geomorphic change on both long and short timescales, to form and change landforms that include but are not limited to gullies/alcove-aprons, dunes, and araneiform terrain.
- (b) Characterize the amounts, form (snow or direct deposition), timing, locations, and evolution of the CO<sub>2</sub> and water frost that is accumulated and removed diurnally and seasonally (within the seasonal cap and down to the lowest latitudinal extent).
- (c) Determine the present rate of activity and the time needed to produce the existing surface features. Detect changes in environmental conditions as recorded within these landforms.
- (d) Characterize interannual variability in active polar surface processes (e.g., jets, spots, avalanches, dune gullies) and determine their relationship to volatile cycles, dust cycles, and weather.
- (e) Determine the existence and present-day extent of possible liquid water within regions with observed surface changes. Are these volatiles driving the observed surface changes?

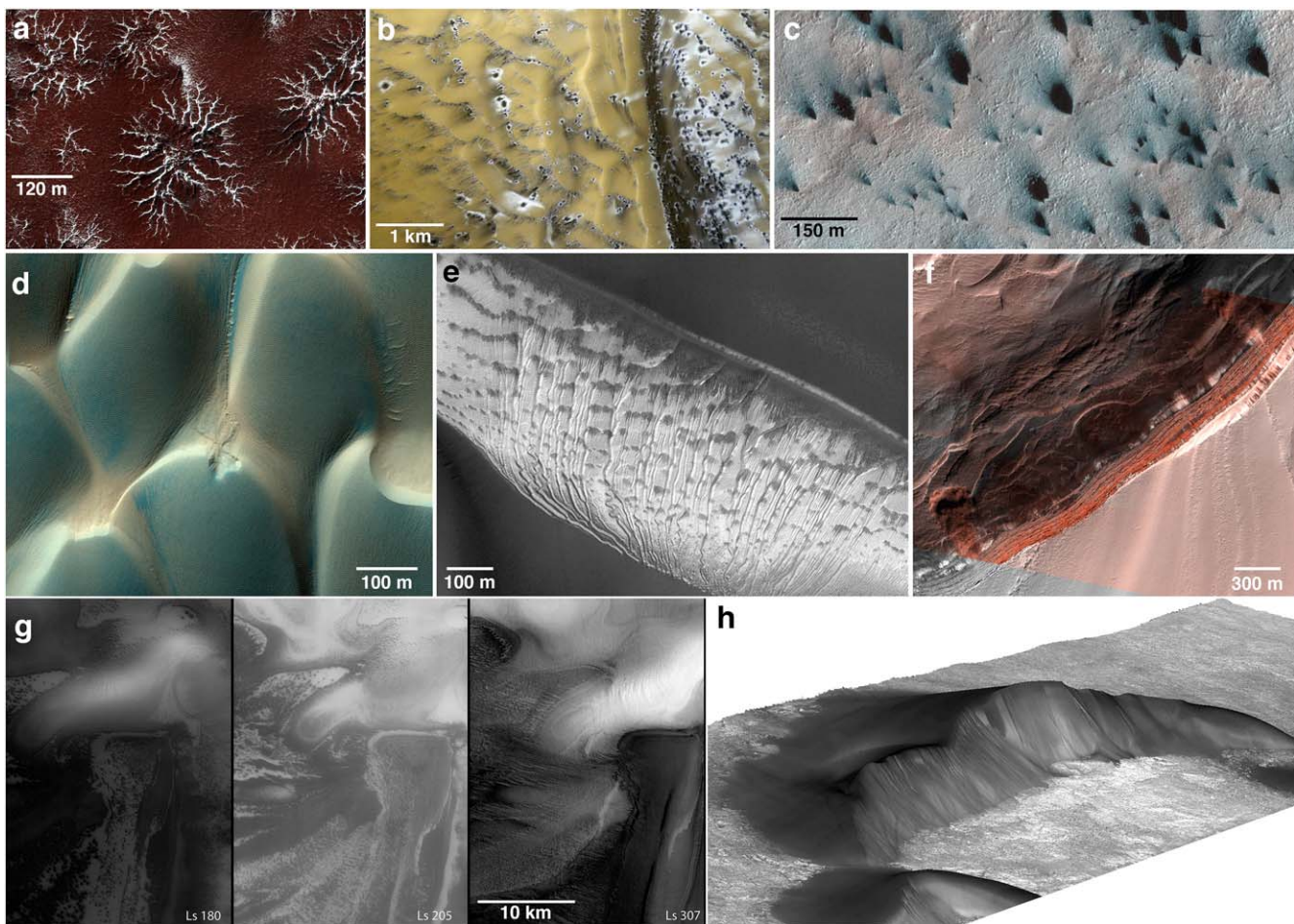
The ice-related activity associated with Martian seasons encompasses some of the most dynamic processes active on Mars today. We have only started to build a coherent understanding of these seasonal processes and their interaction with the climate over decadal timescales. The frequent monitoring of the polar and circumpolar regions by multiple spacecraft for the past two decades has been especially vital for this objective, providing abundant evidence for morphological changes and, in some cases, enabling observations of active processes (Diniega et al. 2021). In the polar and circumpolar regions, the Martian surface exhibits multiple morphological features that are related to its interaction with volatiles during annual and interannual cycles, such as araneiform terrain (Figure 3(a); Hansen et al. 2010, 2013), seasonal spots (Figure 3(b)) and fans (Figure 3(c)), dune alcoves (Diniega et al. 2019), gullies (Diniega et al. 2010; Dundas et al. 2010, 2012, 2019), furrows and avalanches (Figure 3(d)), linear and zigzagging gullies (Figure 3(e); Diniega et al. 2013), polar

scarp avalanches (Figure 3(f); Russell et al. 2008; Becerra et al. 2020b), and other seasonal surface albedo variations (e.g., Figure 3(g)). Some of the geomorphic changes are permanent, and some are of a transient nature, i.e., the surface is modified seasonally in a similar manner year after year. In many cases changes manifest simply as albedo variations, the permanence of which we have yet to understand. Many of the features mentioned above have been hypothesized to be products of seasonal CO<sub>2</sub>-related processes (Kieffer 1979, 2007; Portyankina et al. 2017; McKeown et al. 2021 and references therein), though some may be related to temperature increases in the earliest defrosted surfaces.

The most significant advances in studies of present-day surface activity since the 6th ICMPSE have to do with change detection. As the total time lines of coverage by several remote-sensing instruments grow, so does our ability to detect relatively small annual surface changes. This also aided our understanding of the effects of dust storms on seasonal activity, as having longer time lines means that several dust storms, which are by nature sporadic, have now been covered (Wolkenberg et al. 2020).

Processes that are hypothesized to have a relationship with the Martian dust cycle are related to springtime activity in the polar and circumpolar regions of both poles. The largest-scale surface albedo variations, such as the retreat of the seasonal caps, have been monitored through Mars Years 28–31 (MY; see Piqueux et al. 2015 for information on the Mars calendar) by the MARCI on MRO (Calvin et al. 2015, 2017) and were in general observed to retreat similarly from year to year. Frequent intraseasonal monitoring with CTX and CRISM is helping to explain some of the medium-scale (tens of kilometers) inhomogeneities, such as the evolution of the cryptic region and seasonal ice cover in circumpolar craters (e.g., Figure 3(g); Calvin & Seelos, 2020, 7ICMPSE). The south seasonal cap was observed by HiRISE and CRISM to darken at the onset of spring, but it was also seen to brighten significantly before darkening again until its complete defrosting at the end of the season (Pommerol et al. 2011). Six years of HiRISE observations of the smaller-scale effects of this process have led to the theory that this “spring cleaning” may be either due to wind redistributing a thin dust layer on top of seasonal ice or due to the ice cleaning itself as dust particles sink in sublimating (Portyankina et al. 2010, 2019). Experiments by Schmitt et al. (2020, 7ICMPSE) showed that a more likely explanation for this cleaning is the brightening that occurs during sublimation of slab CO<sub>2</sub> ice as grain boundaries progressively open.

The most iconic representation of seasonal CO<sub>2</sub> processes on both poles is at the smaller scales, through the appearance of sublimation fans, blotches, and generally smaller-scale surface albedo variations (Cesar et al. 2020, 7ICMPSE; Hansen et al. 2020, 7ICMPSE). Fans (Figure 3(c)) are believed to be wind-directed deposits from CO<sub>2</sub> jets generated by insolation-induced basal sublimation of translucent CO<sub>2</sub> ice—a solid-state greenhouse effect known as the “Kieffer model” (Kieffer 2007)—and blotches (Figure 3(b)) represent either similar deposits created in windless conditions or direct surface sublimation markings (Aye et al. 2019). A vast number of images of fans and blotches have been successfully used to derive the speeds and directions of these near-polar winds through a citizen-science effort known as Planet Four (Portyankina et al. 2020a, 7ICMPSE).



**Figure 3.** Present-day, ice-related seasonal surface activity on Mars. All panels are subframes of the complete images. (a) Araneiform terrain in spring (HiRISE image ESP\_020914\_0930; 87°0S, 127°5E). (b) Sublimation patterns (spots, blotches) on southern hemisphere dunes (CaSSIS image MY34\_003098\_264; 72°5S, 172°7E). (c) Seasonal dark fans in the southern hemisphere driven by sublimation (HiRISE image ESP\_011931\_0945; 85°2S, 181°5E). (d) Example of a dune alcove and avalanche in the Buzzel dune field (HiRISE image ESP\_036387\_2640; 84°0N, 233°2E). (e) Two NPLD scarp avalanches caught in action by HiRISE (image ESP\_060176\_2640; 83°8N, 237°E). (f) Zigzagging gullies with seasonal defrosting spots in Aonia Terra (HiRISE image ESP\_019798\_1295; 50°3S, 292°1E). (g) Seasonal variations of albedo on Reynolds crater, as seen by CTX. Seasonal timing increases from left to right ( $L_s$  denotes solar longitude on Mars, with  $L_s = 0$  marking the beginning of the Martian year at northern spring equinox). From left to right: early spring (K05.180523), late spring (K07.180705), and midsummer (K12.181215). (h) Active dune gullies seen in 3D (HiRISE DTM generated from images PSP\_006899\_1330 and PSP\_006965\_1330; 46°7S, 20°1E; the main dune is visible approximately  $6 \times 3 \times 1$  km.  $2 \times$  vertical exaggeration).

The Kieffer model is currently also the best explanation for the formation of dune furrows and araneiform terrain (Hansen et al. 2010, 2013, 2020, 7ICMPSE), which have also been a frequent target of high-resolution observations. However, the present observation baseline has not yet yielded any detection of new erosion of large araneiforms (Figure 3(a); Portyankina et al. 2020b). It is unclear whether the early erosion fluxes are small (and thus require even longer timescales for visual detection) or whether they are currently not expanding. On sand dunes, however, there are detections of newly created araneiform-like troughs (Portyankina et al. 2017), as well as of the repeated appearance and disappearance of small furrows (Bourke 2013). This leads to the generally accepted model that solid-state greenhouse sublimation can create gas flows that erode the surface under current climate conditions. Nevertheless, this might be only applicable under certain circumstances; for example, it may act effectively only in the presence of sandy material aiding the erosion, or only on surfaces with specific properties (McKeown et al. 2020, 7ICMPSE). The possible current stability of large araneiform features would have several implications for the larger picture of Mars Polar

Science: (i) araneiforms are remnants of older, different climatic conditions, and current estimates of the ages of the surfaces into which they are carved are inaccurate (i.e., from Piqueux & Christensen 2008); and (ii) cold  $\text{CO}_2$  jets recycle only the thin top dusty layer from year to year without eroding the underlying surface. If this is the case, estimates of the atmospheric dust load from these jets would also need to be updated.

Though the Kieffer model is generally accepted as an explanation for many of the features explained above, other repeating surface modifications are not fully understood, and there is an ongoing debate about what exact process creates them. A prominent example are the new dune alcoves on high-latitude and polar dunes (e.g., Figure 3(d); Diniega et al. 2020, 7ICMPSE). These alcoves could be created by wind, they can be products of fall/winter  $\text{CO}_2$  condensation and subsequent slope overload, or they can form during basal  $\text{CO}_2$  sublimation in spring through a process similar to the Kieffer model. The timing of appearance of the new alcoves indicates that they are formed between early fall and early spring, and some have been in fact identified to have formed in early fall

(Diniega et al. 2019). This leaves little time for winds to be responsible for their creation, as the ground is covered by frost during that period. Currently, frost-related activities during deposition, during sublimation, or as a combination of the two are more probable candidates (Diniega et al. 2020, 7ICMPSE). Similarly, the exact mechanism that forms linear and zigzag dune gullies (Figure 3(e)) is unclear. Seasonal activity has been observed inside these gullies and on the surrounding surfaces, and gully extensions were also documented (Dundas et al. 2010; Diniega et al. 2010; Reiss et al. 2010; Pasquon et al. 2016). However, the exact mechanism that extends them is currently unknown.

A particularly spectacular seasonal process occurs exclusively in the NPLD, in the form of dust-ice avalanches that have been observed in action for over a decade, cascading down the steep slopes of the NPLD margins during midspring (Figure 3(f); Russell et al. 2008; Becerra et al. 2020b). A likely trigger for these events seems to be the springtime peak in compressional stresses that fractures the scarps (Byrne et al. 2017). Possibly associated with these avalanches is the detection of boulders and blocks that appear to have been dislodged from the BU in areas near where the avalanches have been seen (Fanara et al. 2020). However, this erosion appears to occur later in the year (Herkenhoff et al. 2020, 7ICMPSE), and no blocks have been directly tied to an avalanche event after the latter was detected by HiRISE. Whether these avalanches and block falls nonnegligibly reduce the total mass of the NPLD and whether their erosion outcompetes that of viscous flow (Sori et al. 2016) are still open questions.

The role of water in seasonally active processes is another important open issue. In terms of geomorphology, recently active gullies were historically thought to be caused by the action of water on the surface (e.g., Malin & Edgett 2001). However, the discovery of ongoing activity today has yielded strong evidence that seasonal CO<sub>2</sub> frost is also the major driver in these cases (Dundas 2020, 7ICMPSE). The Kieffer model was again invoked to explain the spectral observations of water ice in the interior of the seasonal cap, which is thermally consistent with CO<sub>2</sub> ice. Titus et al. (2020) suggest that the process of removing the water-ice deposits starts with a Kieffer process, but instead of forming jets, the sublimated CO<sub>2</sub> “seeps” upward into the interface between the two ices, increasing pressure until the cold-trapped water ice is fractured. Small fragments of this water ice would be suspended, while larger fragments would agglomerate. In a separate but related effort to track the exchange of water between the atmosphere and the regolith, Hu (2020, 7ICMPSE) simulated the variation of D/H at the boundary layer. Their results show that D/H can vary by 300‰–1400‰ diurnally in the equatorial and polar locations, but that this value is even greater at colder locations or seasons.

Finally, winds also play an important role in shaping the current landscape. In the north polar region, the action of winds leads to high rates of dune migration within the north polar erg (Chojnacki et al. 2020, 7ICMPSE). Additionally, numerous dust devils occur as far south as 65°N, which leave tracks that have been used to derive wind directions in this region (Tamppari et al. 2020, 7ICMPSE). The characteristics and variability of wind direction on Mars are not well constrained; the Mars community identified these topics as a persistent need.

*Question 6: Mars as a test bed for comparative planetology: What are the similarities and differences between the geologic,*

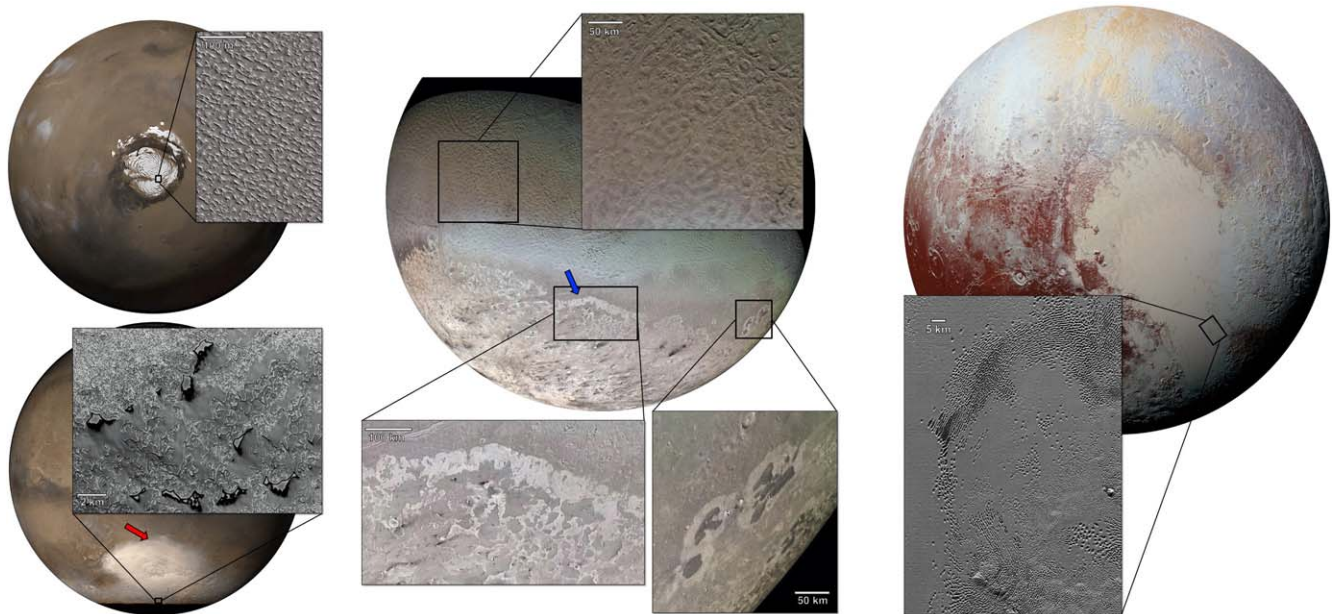
*atmospheric, and climatological processes that affect planetary bodies with surface ices?*

- (a) Quantitatively characterize how orbital, planetary, and environmental controls affect planetary geomorphological evolution by identifying and modeling relevant surface processes that are similar across bodies (e.g., the formation and evolution of seasonal ice caps composed of the solid phase of the main atmospheric component).
- (b) Identify Martian landforms that are formed through volatile accumulation or sublimation-driven processes and that may have analogous features on other planetary bodies.
- (c) Determine the extent to which ice-related surface processes on other planetary bodies may be analogous to those on Mars (e.g., the formation of seasonal frost caps).
- (d) Determine the commonalities of the role of orbital/axial forcing on climate variability within the planetary systems that share attributes with Mars but have different atmospheres, volatile compositions, thermal conditions.

Stimulated by the interdisciplinarity of Mars Polar Science and by the increased interest in the study of ices across the solar system, the need for a dedicated space in this road map for comparative “cryospheric planetology” was identified. As a result, in this paper we add a sixth top-level question that seeks to inspire a future increase in comparative work and defines subquestions that motivate common research themes within the context of comparative Mars Polar Science. In addition, two white papers by conference participants were submitted to the NASA decadal survey that frame Mars (Diniega et al. 2021b) and its cryosphere (Smith et al. 2021b) as planetary laboratories for the study of a variety of processes on other planets.

Similarities between the Martian climate and cryosphere and their counterparts on Earth have been discussed in Questions 2 and 3 above and are further exemplified in Section 3.4. However, the Martian system also shares many characteristics with other planetary bodies. Mars is the best studied and most accessible of the bodies in the solar system in which the major atmospheric component condenses onto the surface (McKinnon & Kirk 2014). Triton and Pluto have seasonal and permanent sheets of N<sub>2</sub> ice on their surface (Figure 4), which have been compared to the seasonal and residual CO<sub>2</sub> ice caps of Mars. Seasonal sublimation–deposition resurfacing cycles may also be a dominant surface process on other Kuiper Belt bodies, such as Eris (Hofgartner et al. 2019). On Io, the SO<sub>2</sub> atmosphere is at least partially sublimation driven and is thus in continuous interaction with SO<sub>2</sub> frost on the surface (Walker et al. 2010).

Research into the parallels of “CO<sub>2</sub>-based” Mars with “N<sub>2</sub>-based” Pluto and Triton has seen a rise since the New Horizons spacecraft revealed extraordinary details about the surface of Pluto. Sublimation-driven features in Pluto’s N<sub>2</sub> ice sheet “Sputnik Planitia” have been contrasted in both morphology and formation theories with features on the North and South PRCs of Mars (Moore et al. 2017; Buhler & Ingersoll 2018). The observation of craters acting as cold traps for volatiles on Mars (Conway et al. 2012) has inspired similar explanations for ice deposits in depressions on Pluto. The physical processes that lead to CO<sub>2</sub> condensation in Mars’s Hellas basin (Figure 4, left panel) are the same as those in



**Figure 4.** Examples of comparative icy planetology. Left panels: MOC composite images of Mars’s polar regions. The top left panel is centered on the north polar region, and the inset shows a HiRISE view of the patterned texture of the NPRC. The bottom left panel shows the persistence of the seasonal south polar ice cap in Hellas basin in midspring (red arrow). The inset shows a CTX image of the iconic “swiss cheese” terrain, farther south on the SPRC. Middle panels: Voyager 2 photomosaic of Triton. The main image shows the extent of Triton’s south polar seasonal cap of nitrogen ice, extending almost to equatorial latitudes (blue arrow). The insets are zoomed-in views of cantaloupe terrain in the northern hemisphere (top), the margin of the seasonal cap with sublimation features (bottom left), and zoned maculae (bottom right). Right panels: New Horizons composite view of Pluto’s heart-shaped nitrogen ice sheet Sputnik Planitia. The inset shows sublimation pits (Figure 3 of Moore et al. 2017).

Pluto’s Sputnik Planitia; higher surface pressures within the basins compared to the surroundings result in higher condensation temperatures (Bertrand & Forget 2016). The many circumpolar craters on Mars that host layered ice mounds are strikingly similar to craters on Pluto that surround Sputnik Planitia and also appear to contain volatile deposits in their interiors. This may mean that similar records of Plutonian climate may exist in these craters, as they do on Mars (Sori et al. 2019). Furthermore, the evolution of glacial flow on Mars’s MCID (Smith et al. 2021b) and that of Pluto’s glacial landforms (Umurhan et al. 2017) are also notably analogous.

Correspondence between the environments of Mars and Triton has been discussed since the days of the Voyager missions. Triton’s  $N_2$  atmosphere (like Pluto’s) is in vapor pressure equilibrium with surface ices and, like Mars’s  $CO_2$  atmosphere, will form seasonal ice sheets. The near-hemispheric extent of its  $N_2$  ice sheet (Figure 4, center) sheds light on its heat flow, which leads to parallels being drawn between Martian and Tritonian environments, while differentiating the evolution of the ice sheets through the contrasts in ice rheology and conductivity (Sori 2021, and references therein). Moreover, plumes and fan deposits seen by Voyager on Triton’s surface were proposed to be driven by a solid-state greenhouse effect (though recent work suggests that endogenic processes could also explain them; Hansen et al. 2018; Hofgartner et al. 2018), and in fact inspired the Kieffer model for the Martian jets (Kieffer 2007).

There are also many geomorphological parallels between Mars and other bodies. The thermal equilibrium between volatiles and their ice phases on the surface leads to similar surface features on Pluto and Mars, such as sublimation pits (Figure 4). Central-pit craters are common on bodies with volatile-rich crusts such as the Galilean and many Saturnian satellites, but they also exist on volatile-poor bodies like the

Moon and Mercury. Central-pit craters on Mars (with a volatile content in between the two) were used to establish many dependencies in the characteristics of central-pit craters with planetary size and volatile content (Barlow et al. 2017). The bright central dome of Occator crater on Ceres has been suggested to be analogous to pingos (frost mounds) on Earth and Mars, which form by groundwater migration and freezing (Schenk et al. 2019). Finally, recent mapping of the morphological properties of chaos terrains on Mars, Pluto, and Europa led to inferences about crustal lithology and surface layer thickness (Skjetne et al. 2021).

Comparative planetology between Mars, Pluto, Triton, etc., has thus produced important advances in our understanding of each body. It is important to maintain this approach while also acknowledging the differences in composition and environment. Furthering noncomparative research into the ice rheology, glacial flow, and surface–atmosphere interactions of the specific ices in each body—particularly those in vapor pressure equilibrium with the atmosphere—will be invaluable to fully grasp their behavior and geomorphic effects. In the process, however, maintaining a comparative perspective ensures that knowledge gained from one body can continuously inform hypotheses about the others and incrementally elucidate the relationships between ices and the climates and surface morphology of their parent bodies.

The variety and impact of the research summarized above confirm the applicability and importance of Mars as a global-scale laboratory for the study of numerous planetary processes, as it is one of the more accessible targets for exploration in the solar system. The subquestions defined here align with many of the open questions generated by prior work and as such will drive the advancement of future studies within the same context. We envision that such studies will be presented and discussed in future editions of the ICMPSSE.

### 3. Progress and Future of Research Methods

Throughout ICMPSSE history, the in-depth, interdisciplinary discussions at the meetings have resulted in many multifaceted solutions to specific issues of Mars cryospheric science. In this section, we summarize the current progress and the recommended advancements identified by the community regarding mission data acquisition and measurements, modeling, field-work, and laboratory work. When necessary, we reemphasize some of the progress that was mentioned in the previous section, in order to tie a scientific theme to methodologies necessary for advancement within that theme.

#### 3.1. Missions and Measurements

The significant advances in Mars Polar Science made possible by the data from completed and currently operating missions were heavily featured throughout the conference presentations and are well summarized in the sections above. Still, a relatively new data set that has yet to be fully explored to study Martian ice comes from ExoMars TGO's CaSSIS (Thomas et al. 2017, 2020; 7ICMPSE) on board ESA's TGO. Though the orbit of TGO does not allow images higher than  $\sim 75^\circ$  absolute latitude, many nonpolar and even circumpolar studies will benefit from this data set. For example, the northernmost margin of the SPLD's Ultima Lingula region can be imaged in stereo at a high frequency, allowing for a detailed stratigraphic study of over 500 km of exposed bedding (Becerra et al. 2019). Similar topography-based stratigraphic mapping can be performed on the icy layered deposits in circumpolar craters around the south and north polar regions (Sori et al. 2019). Additionally, multispectral CaSSIS images may be used to characterize lower-latitude exposures of surface and buried ice (Tornabene et al. 2021).

The advances presented throughout the conference raise new questions, some of which can only be addressed by measurements from future missions. In the years since the 6th ICMPSSE, several assessment reports and mission concept studies were arranged to determine the best approaches to answer many of the central questions to Mars Polar Science (MEPAG NEX-SAG 2015; MEPAG ICE-SAG 2019). A KISS workshop (Smith et al. 2020) inspired a NASA 2019 Discovery mission proposal (COMPASS) for a climate-and-ice-focused orbiter mission that addresses some of the key knowledge gaps related to the polar record (Byrne et al. 2020, 7ICMPSE). Additionally, two Mars-climate-related proposals—MORIE (Calvin et al. 2021) and MOSAIC (Lillis et al. 2020)—were carried out through the 2019 Planetary Mission Concept Studies program. In addition to the ICE-SAG summary that launched the 7th ICMPSSE, many of the findings of these reports were at the forefront of discussion during the conference. Other possibilities for relevant technology development, data use, landed mission site selection, and dedicated ice-and-climate-or ice-and-astrobiology-focused mission concepts were also presented and were later the focus of white papers submitted to the NASA Decadal Survey.

In terms of in situ measurements, ice core extraction through drilling is undoubtedly the best way to obtain detailed compositional information from an ice sheet record. The importance of drills on static and mobile landers for Mars cryospheric science is explicitly mentioned in the ICE-SAG report (Concept NF1 in MEPAG ICE-SAG 2019), and a few drilling concepts were discussed at the conference. A dual-

architecture rover/lander mission is currently undergoing analog tests in the Atacama Desert (Glass et al. 2020, 7ICMPSE), and technologies envisioned for in situ ice core analysis, such as microCT, are also under development (Obbard et al. 2020, 7ICMPSE; Sarrazin et al. 2021). In addition to their obvious advantages for ice coring, drills have the ability of assessing the habitability of subsurface ice environments. This is the focus of astrobiology-focused cryospheric mission concepts, such as the Ice-Breaker mission, which was also proposed to the 2019 NASA Discovery mission call (Stoker & Noe Dobrea 2020, 7ICMPSE). Another interesting in situ concept for this purpose is using vibration sensors that can sense nanovibrations caused by the metabolic activity of microorganisms (Johnson et al. 2020, 7ICMPSE). These instruments would work in tandem with drills and support stratigraphic and astrobiological investigations. Finally, an assessment of the potential of polarization measurements to detect the presence of amino acids in ice determined that, although the method is convenient for use in an in situ lander, its detection thresholds are currently too high compared to other methods; thus, further research is warranted (Cook et al. 2020, 7ICMPSE).

From orbit, a higher-frequency (200–2000 MHz) orbital sounding radar has been almost universally accepted by the Mars ice community as a primary need within the next decade (Lillis et al. 2020; Bramson et al. 2021; Calvin et al. 2021). The COMPASS Discovery mission proposal (Byrne et al. 2020, 7ICMPSE) featured a dual-mode SAR-sounder radar that would have addressed this need. Though not selected, many of the science objectives and instruments (e.g., the dual-mode radar) of COMPASS are also incorporated in the Mars Exploration Ice Mapper mission concept, the purpose of which is explicitly to search for habitable environments and accessible ISRU resources in the Martian ice (Watzin & Haltigin 2020).

Another orbital measurement set that has been recognized by MEPAG reports (e.g., NEX-SAG 2015; ICE-SAG 2019) and within the ongoing Decadal Survey white paper submissions (e.g., Guzewich et al. 2021; Tamppari et al. 2021) is the need for vertical profiles of both vector wind and water vapor. Wind measurements are needed to validate the global circulation models upon which current research heavily relies, and the combination of wind and water vapor measurements would go a long way toward determining the present-day vapor transport. This, in turn, would help unravel the temporal history of the PLDs.

Naturally, none of the current progress would be possible without orbital imaging. Thus, continuing the very successful, currently operating orbiter missions (MRO—highest-resolution imaging of Mars to date—TGO, Odyssey, Mars Express, MAVEN) and further extending high-resolution orbital imaging, spectroscopy, and stereo topography of Mars are also considered critical to the questions above and to all of Mars science (MPAG NEX-SAG 2015; Concept NF5 in MEPAG ICE-SAG 2019; Smith 2020; Lillis et al. 2020; Calvin et al. 2021; Diniaga et al. 2021).

The benefits of Unoccupied Aircraft Systems (UASs) for Mars Polar Science are also being explored (Bapst et al. 2021). Next-generation Mars UAS designs (Johnson et al. 2020) are being analyzed to follow up on the successful flights of the Ingenuity helicopter that accompanies the Mars 2020 Perseverance rover. Solar-powered, next-generation rotorcraft concepts could range from 5 to 30 kg in mass and can potentially carry

up to 5 kg of science payload. UASs can travel >10 km in a single flight, allowing for mission traverses on the order of >100 km, well beyond the capability of current rovers. Not only can a UAS explore terrain that would be otherwise inaccessible, but it also moves through the boundary layer (up to 2 km above the surface), allowing in situ measurements of the atmosphere and its constituents. These enabling aspects of a UAS are aligned with many of the goals of Mars Polar Science, and therefore aerial platforms should be considered as a means of exploring the polar and icy terrains of Mars.

Finally, midlatitude ice deposits have garnered a great deal of attention in the past few years, not only because of their scientific importance but also due to their potential for ISRU by future crewed missions. Interest in human exploration and settlement of Mars is rapidly increasing, with SpaceX (Wooster et al. 2018), NASA, ESA, and CNSA all making plans for near-term missions. Human explorers will likely target flat landing sites (slopes <5°) that are relatively free of large boulders and dust, but which also have relatively easy accessibility to water. At the 7th ICMPSSE, McEwen et al. (2020, 7ICMPSE) proposed a site in Phlegra Montes that fulfills all of these requirements and is an ideal landing location for a human mission. Sites in Phlegra Montes, Erebus Montes, and Arcadia Planitia have been proposed as downselected SpaceX Starship landing sites (Golombek et al. 2021). In addition, technologies are currently under development for extraction and ISRU of shallow water deposits for human explorers. Hoffman et al. (2020, 7ICMPSE) demonstrated the theoretical feasibility of a technique known as a Rodriguez Well, which would melt the ice, store the resulting water in a subsurface ice cavity until needed, and then pump water to the surface for use.

### 3.2. Modeling

*Orbital mechanics:* Recent work revisiting Mars's orbital evolution has challenged the canonical view that the planet's orbit is chaotic, suggesting instead that dissipation may suppress chaos (Bills & Keane 2019). Crucially, initial results of this model do not predict an abrupt change in Mars's obliquity regime at ~4 Ma, which is predicted by the chaotic model (Laskar et al. 2004) and is widely regarded to have triggered the formation of the NPLD (e.g., Levrard et al. 2007).

Ascertaining whether Mars's orbital evolution is dissipative is crucial for determining quantitative timescales in the climate record. Existing observation tests, such as analyzing ratios in frequencies of layer properties (Becerra et al. 2017, 2019), cannot differentiate between a chaotic and dissipative evolution because both theories predict similar timescales for the variation of different orbital elements. Although other observations, such as the elliptical crater record (Holo et al. 2018), may have more distinguishing power, the dissipative model requires further development in order for its prediction of no change in the obliquity regime at 4 Ma to be tested.

*Global climate models (GCMs):* GCMs are indispensable tools to understand the current and past Martian climate, and thereby the Martian cryosphere. Since the 6th ICMPSSE, GCMs have begun using significantly higher temporal and spatial resolutions, incorporating new physics, and, most importantly, assimilating new data (e.g., Streeter et al. 2020, 7ICMPSE). More capable GCMs show that radiatively active clouds have a profound influence on the water cycle in both polar and midlatitude regions (Kahre & Haberle, 2020, 7ICMPSE; Kuroda 2020, 7ICMPSE; Naar et al. 2020, 7ICMPSE). GCM simulations covering large

regions of orbital parameter space have advanced knowledge of historical water and dust flux into the polar climate record and emphasized the importance of ice-on-dust nucleation in polar deposition (Emmett et al. 2020). Furthermore, recent efforts to model the D/H signature of volatile deposits have advanced enough to link orbital periodicities with modeled isotopic signals (Vos et al. 2019) and predict testable, present-day diurnal variations (Hu 2020, 7ICMPSE). This could provide an important constraint on the interpretation of the climate record that is complementary to the physical and compositional record. This continued sophistication of GCMs is essential for understanding the polar mass flux and establishing appropriate interpretations for the polar climate record.

*Landscape evolution:* Modeling of landform development driven by ice-related processes is important for understanding the mesoscale interactions between the CO<sub>2</sub>, water, and dust cycles that determine volatile-deposit mass balance and incorporation of material into the climate record. Smith et al. (2018) highlighted the need for models of landscape evolution to explain residual-ice-related geomorphologies (both CO<sub>2</sub> and water). Advances since the 6th ICMPSSE have directly addressed this need.

In the CO<sub>2</sub>-dominated south polar region, a process-based model of SPRC development (Buhler et al. 2017) and a probabilistic diffusion model of araneiform terrain development (Portyankina et al. 2020b) both produce good agreement with observed morphologies. In the north, a conceptual model of water lifting driven by CO<sub>2</sub> sublimation on the surface of the NPLD (Titus et al. 2020) can likely explain north polar seasonal cap retreat rates. Importantly, new quantitative landform models appear to explain and date the development of the texture of the NPRC surface (Wilcoski & Hayne 2020). Further, scaling laws derived from theoretical models can study ice surface-atmosphere interactions to explain the development of the small-scale periodic surface features that are the basis of this surface texture (Bordiec et al. 2020). It is clear that progressive maturation of physics-based numerical models for ice-driven landform evolution (e.g., Hvidberg et al. 2012; Byrne et al. 2015; Wilcoski & Hayne 2020) are essential to understand how climatological conditions form a layer in the stratigraphic record. Continuing this progression will enable us to further our knowledge about aspects of the state of past climates that are recorded in the ice stratigraphy.

*Rheology and flow models:* Qualitative rheologic modeling suggests that viscous flow rates in the NPLD and SPLD may be low owing to the retarding effects of thin layering (Smith 2020, 7ICMPSE). Additionally, mass wasting appears to outpace viscous relaxation even on nearly vertical NPLD scarps (Sori et al. 2016; Fanara et al. 2020). Continued investigation of ice flow in the PLDs is important for understanding the extent to which post-depositional flow has modified the climate record. In addition, models of the dynamics of ice and ice-mixture dynamics under Martian conditions are necessary to develop our understanding of midlatitude glacial landforms (e.g., LDAs; Serla et al. 2020, 7ICMPSE).

*Thermal models:* The role of lag layers in regulating volatile transfer has emerged as a significant open question in our effort to model and interpret Mars's climate history. Recent models show that the thermal insulation of ice by dust lags can aid in preserving midlatitude ice sheets for many millions of years, much longer than obliquity cycles, although some loss is still expected during periods of low obliquity under nominal conditions (Bramson et al. 2017).



Lag layers may also be responsible for the apparent surface-age difference between the SPLD and NPLD (Herkenhoff & Plaut 2000; Landis et al. 2020, 7ICMPSE). If lag layers are effective at inhibiting change between volatile reservoirs, this may complicate efforts to model the transfer of ice between the north and south polar regions, midlatitudes, and equatorial regions (Levrard et al. 2007; Patel et al. 2020, 7ICMPSE; Vos et al. 2020, 7ICMPSE). Importantly, atmospheric water vapor content plays a crucial role in the stability of ice deposits, and the quantities and distribution of water vapor within the atmosphere, now and in the past, are necessary inputs for modeling ice stability. Recent work on this topic shows that water vapor is concentrated near the surface at the Phoenix landing site (Tamppari & Lemmon 2020), which would enhance preservation of subsurface and surface ice deposits. Such ice retention is supported by the observed latitudinal range of subsurface ice at new impact sites, which is consistent with elevated near-surface humidity values and/or long-term average atmospheric water contents above that at present day (Dundas et al. 2014). The permeability of MCID lag layers to CO<sub>2</sub> flux also requires further research; whether the MCID lag is permeable or nonpermeable would significantly affect Mars's Amazonian obliquity-driven surface pressure cycle (Manning et al. 2019; Buhler et al. 2020a).

*Subglacial liquid:* Numerical models that tackle much of the physics and geology discussed above (e.g., thermal, rheological, landscape evolution) will need to be specifically focused on studying the bright basal radar reflections beneath the south polar cap that have been interpreted to be liquid water (Orosei et al. 2018; Lauro et al. 2021). A recently published model does not predict stable liquid water without higher-than-expected geothermal heat input or enhanced salt concentration (Sori & Bramson 2019). While this scenario is not out of the question, similarly bright radar reflections have also been observed across extensive regions of the SPLD, where they were not interpreted as derived from liquid water (Plaut et al. 2007). Thus, further investigation should focus on modeling other physical scenarios for water stability and on further characterizing radar scattering phenomena to fully explore the parameter space that could lead to such bright basal radar reflections.

### 3.3. Fieldwork and Terrestrial Analogs

The study of terrestrial glacial and periglacial processes with the objective of learning about Martian ice has been a staple of Mars Polar Science since the first comparisons were made between flow-like features on Mars and terrestrial glaciers (i.e., Kargel & Strom 1992). This approach continues to improve our understanding of ice-related processes on Mars and is becoming increasingly important for future exploration as we require accessible analogous testing grounds to evaluate new instrumentation. During the 7th ICMPSE, many participants presented progress related to identifying, characterizing, and utilizing Mars-analog sites on Earth.

Geomorphology-based analog investigations compare the morphology and morphometry of terrestrial and Martian landforms and evaluate their similarity, as a means to draw interpretations regarding the origin of Martian glacial features. For example, polygonal terrain is the most ubiquitous landform in the midlatitudes of Mars, and it is analogous to polygons found in the polar deserts of the Arctic and Antarctic, high mountain environments, and warm desert environments (Sager et al. 2021) on Earth. Though polygonal terrain on Earth often indicates the presence of frozen (or once frozen) ground, the

relationship between polygon morphology and ice volume fraction and depth is not well constrained.

There is ongoing discussion regarding the state of evolution and ice content of Martian polygons, which has major implications for past climate interpretations and the current presence of near-surface ice. Polygonal terrain has the potential to host a substantial amount of near-surface ice if polygonal cracks are filled with ice or if polygonized soil overlies laterally extensive excess ice, as was observed at the Phoenix landing site (Mellon et al. 2009). Knightly et al. (2020, 7ICMPSE) tested a periglacial origin hypothesis through UAV-based photogrammetry of relict and active periglacial patterned ground sites, comparing their micro-morphology to patterned ground at the Phoenix landing site. However, a range of mechanisms, including some unrelated to ice, may produce similar polygonal morphologies. For example, polygonal networks may form owing to desiccation cracking and salt weathering processes alone in desert environments (Cheng et al. 2021; Sager et al. 2021). Continued study of polygonal terrain on Earth will improve our understanding of these features on Mars and provide insights into its subsurface and atmospheric conditions and past climate.

“Brain terrain” is another common landform found in the midlatitudes of Mars that has been suggested to form via ice-related processes based on analogous periglacial and glacial landforms on Earth (Levy et al. 2009). Until recently, only limited examples of potential analogous landforms to “brain terrain” on Mars could be studied on Earth. In the Canadian High Arctic, Hibbard et al. (2020, 7ICMPSE) identified a morphologically analogous feature to Martian brain terrain that is hypothesized to form via periglacial and/or glacial processes. Yet Cheng et al. (2021) identified different analogous brain-terrain-like landforms in the Qaidam basin that they instead suggested form through aeolian and salt-related processes. Further study of these unique Earth analogs could help explain how brain terrain forms on Mars and whether a relationship with ice must necessarily be present.

The combination of geomorphological analyses with process modeling has produced notable results. For example, Spagnuolo et al. (2020, 7ICMPSE) modeled the thermal environment of Hale crater and recognized a correlation between poorly illuminated areas and glacial features that were identified based on analogous Icelandic glacial landforms. Applying terrestrial models to Martian conditions can also guide the manner in which analogs are used. For instance, there is a general lack of clear evidence of wet-based glacial erosion on Mars, which has historically supported the hypothesis that Martian glaciation was largely cold-based (Fastook & Head 2015; Wang & Yin 2020, 7ICMPSE; Yin & Wang 2020, 7ICMPSE). However, through modeling and comparisons with terrestrial subglacial landforms in the Canadian Arctic, Grau Galofre et al. (2020) found that the motion of wet-based ice masses under Martian gravity may produce landforms more akin to those found in terrestrial thin, cold polar ice caps than those commonly attributed to continental ice sheets. Additionally, Gallagher et al. (2021) recently identified the widespread existence of landforms suggestive of warm/wet-based glacial erosion in over 16,000 km<sup>2</sup> of VFFs. These investigations indicate that continental-scale wet-based glaciation may have been a possible landscape modification agent on ancient Mars.

Although Earth is a more active planet than Mars, the study of currently active processes on Earth can influence interpretations of certain features on Mars. Hvidberg et al. (2020, 7ICMPSE) are using Landsat 8 images and field studies to

evaluate the dependence of ice–atmosphere interactions on surface patterns observed on the Greenland Ice Sheet with a goal of gaining insight into atmospheric processes on Mars from icy terrains. The study of terrestrial ice sheets is essential to understanding Martian and other planetary climate records. As such, continued collaboration between the terrestrial glaciological community and the Mars cryospheric community is highly encouraged (Yoldi et al. 2020, 7ICMPSE).

Geochemical analog studies can also provide important insight into Martian history. For example, Rutledge et al. (2020, 7ICMPSE) found that the alteration mineralogy of terrestrial glacial environments contrasted with the mineralogy of Martian Noachian terrains and suggested that these terrains on Mars must have undergone aqueous alteration during persistent warm periods, in contrast to some cold-icy models of Noachian climate.

The use of GPR on terrestrial glacial features with specific Mars-oriented goals has also seen a rise. It has led to understanding debris-covered glaciers on both Earth and Mars (Petersen et al. 2020, 7ICMPSE; Meng et al. 2020, 7ICMPSE) and to improving GPR-based 3D models of subsurface ice on Earth, with the goal of applying them to Martian subsurface ice bodies (Andres et al. 2020, 7ICMPSE). GPR-based research in Mars Polar Science is especially relevant and valuable given (1) the presence and continued operation of SHARAD and MARSIS; (2) the RIMFAX and WISDOM GPRs on the Perseverance and Rosalind Franklin rovers, respectively; and (3) the push for a higher-resolution orbital radar by the Mars ice community (MEPAG ICE-SAG 2019; Lillis et al. 2020; Becerra et al. 2021; Bramson et al. 2021; Calvin et al. 2021; Smith et al. 2021a).

Finally, terrestrial analogs can also contribute to technological developments in preparation for spacecraft exploration. Funding programs like NASA’s PSTAR promote these efforts and have resulted in Mars-ice specific technologies, such as a dedicated rover studying sediments in Iceland (Sinha et al. 2020, 7ICMPSE) and drill systems being tested in the Atacama Desert in Chile (Glass et al. 2020, 7ICMPSE).

The importance and relevance of analog fieldwork are made clear by the contributions mentioned above and the outlook of the community. We therefore encourage further field analog investigations and recommend increased collaboration with the terrestrial glaciological community.

### 3.4. Laboratory Work

Laboratory measurements are often the only way to perform detailed studies of ices and processes that have no terrestrial analogs (Smith et al. 2018), and they provide a best-estimate ground truth for many spacecraft measurements. Experimental data are required to correctly interpret remote-sensing observations and to constrain numerical models.

During the past few decades, the planetary community has developed several facilities dedicated to the study of extra-terrestrial ices. Examples of these are the Ice Lab (University of Bern, CH; Pommerol et al. 2019), the Aarhus wind tunnel simulator (Aarhus University, DK; Merrison et al. 2008), the Cold Surfaces Spectroscopy laboratory (Institut de Planétologie et d’Astrophysique de Grenoble, France; Beck et al. 2017), the Mars Simulation Chamber (Open University, UK; McKeown et al. 2021), the laboratory for clathrates spectroscopy (Laboratoire de Planétologie et Géodynamique de Nantes, FR; Oancea et al. 2012), and the Laboratory for Dielectric,

Imagery, and Cryogenic Experiments (DICE, York University, CA; Karimova & Smith 2021).

These laboratories have yielded results directly relevant to Mars Polar Science, many of which were presented at the 7th ICMPSE. CO<sub>2</sub> ice phenomena have only rarely been studied inside a laboratory setting, but recent lab-based studies have simulated CO<sub>2</sub>-sublimation/condensation-driven processes (Kaufmann & Hagermann 2017; Chinnery et al. 2018; McKeown et al. 2020, 7ICMPSE; Karimova & Smith 2020, 7ICMPSE). Experiments on CO<sub>2</sub> ice reflectance, morphology, and mechanics are currently helping us understand dark polar spots (Cesar et al. 7ICPMSE), the albedo increase of Mars’s seasonal caps (Schmitt et al. 7ICPMSE), and ice-rupture processes (Kaufmann et al. 2020). However, dry ice studies are not the only focus of Mars polar experiments; e.g., Herny et al. (2020, 7ICPMSE) simulated wind-driven transport of ice particles under Martian conditions to suggest a possible aeolian origin for many surface features on the NPRC.

Despite these valuable efforts, the need for empirical data regarding the Martian ices and their related processes remains. The community explicitly recommended increasing laboratory studies that specifically focus on Martian polar processes, emphasizing the following:

- (a) CO<sub>2</sub> ice experiments: CO<sub>2</sub> interaction with water ice, dust, and salts is still poorly understood in the context of Mars cryospheric processes. Further constraints on the optical, physical, and rheological properties of CO<sub>2</sub> ice and its mixtures are necessary.
- (b) Lab-based spectroscopy: The substantial enrichment of a spectral database of endmembers and various mixtures involving ices in different physical conditions (pressure, temperature, humidity), in different states (slab, granular, snow), and with varying contaminants (dust, salts, etc.) is necessary (Yoldi et al. 2020). This is crucial to understand the evolution of ice deposits via ice metamorphism, cracking, and sublimation and would in turn help constrain ice accumulation and ablation. It is also necessary to understand ice stability at lower latitudes and the presence of liquid water on the planet, since the presence of contaminants in the ice would affect its thermodynamic properties.
- (c) Interaction between ice and Martian sediments: small improvements to our understanding in this regard could have major effects in all areas of Mars Polar Science. Dust in ice affects the rates of gas exchange between the ice and the regolith, affecting the rates of formation of a dust lag/mantle that inhibits ice sublimation/condensation and influences surface processes and ice stability. The stability of the ice at different latitudes is highly dependent on its albedo and thermal inertia, which motivates lab-based studies of lag formation/erosion mechanisms. In addition, further morphological experiments are necessary to constrain how ice sublimation might provoke sediment transport and shape the Martian surface (e.g., gullies, dune alcoves, jets, and spiders; Sylvest et al. 2016; McKeown et al. 2017).
- (d) Aeolian transport: Wind plays an essential role in shaping the Martian polar regions (Howard 2000). Thus, wind tunnel experiments are needed to understand the interaction between wind, sublimation, and particle transport (ices and sediments).

- (e) Ice rheology: Investigations into the flow of ice under Martian conditions are necessary to fully understand the history of the polar caps (Smith 2020, 7ICMPSE) and their current activity (Russell et al. 2008; Sori et al. 2016; Fanara et al. 2020), as well as the emplacement and evolution of nonpolar glacial deposits (Grau-Galofre et al. 2020; Serla et al. 2020, 7ICMPSE).
- (f) Large-scale experiments: Although experiments at a large scale are less frequent, they often provide insight that other settings cannot, and are thus encouraged. These experiments can help understand radar observations of ice layers through controlled-environment measurements (Carter et al. 2016) and better evaluate sublimation as a geomorphological agent under Martian conditions (Massé et al. 2016; Heryn et al. 2018).

#### 4. Concluding Remarks

It has been over two decades since a “Mars Polar Science” community established itself in the first ICMPSE. In this time, the community has grown considerably, expanding to many corners of the world and many subfields of science. In part as a result of this expansion, research within the field has led to some of the most groundbreaking discoveries in planetary science.

The progress since the 6th ICMPSE in Iceland has been staggering. We have improved our understanding of surface-atmosphere interactions at the poles through multiyear monitoring and were able to essentially track the effects of a PEDE on the cryosphere “live.” Our interpretation of the PLD record has steadily advanced, to the point that we have been able to estimate the timing of formation of specific unconformities and layer packets in both the upper units of the NPLD and the CO<sub>2</sub> units of the SPLD. New theories have emerged, such as the hypothesis that liquid water pockets could exist beneath the SPLD. Our inventory of ices on Mars has grown substantially, especially in the midlatitudes, where continuing research will most likely play a central role in the eventual selection of the first human landing site on Mars. In addition, through the study of present-day activity, we have cemented the current picture that Mars is truly an active planet, and we are establishing the notion that CO<sub>2</sub> frost and ice is the preeminent agent of change on the Martian surface today. Finally, the many years of study that have been dedicated to Mars polar and cryospheric science have allowed us to better frame the field in the overarching context of comparative planetology, which will likely lead to exciting new discoveries not only on Mars but also on many other planetary bodies in our solar system, and perhaps beyond.

As is usual in all scientific endeavors, more answers generate more questions, so there is much work yet to be done. As a community, we hope to see our open questions considered in top-level discussions in space agencies around the world so that many of the mission concepts, instrument developments, and measurements presented here can be realized. These concepts for missions and investigations are designed to answer the main open questions in the field of Mars Polar Science, which, as we have demonstrated here, are important for all areas of planetary science and exploration.

This paper serves as a guide for the research goals of the Mars Polar Science community, in particular for the next 4 yr, after which the next ICMPSE is anticipated to be held. We are












certain that the following 4 yr will bring a great deal more progress and discovery, and we look forward to the presentations, discussions, answered questions, and new open issues that will be addressed in the 8th ICMPSE.

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