The state of the Martian climate

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SIDEBAR 2.1: THE STATE OF THE MARTIAN CLIMATE—P. L. READ, S. R. LEWIS, AND D. M. KASS

The Martian Atmosphere

In terms of its atmosphere and climate, Mars is the planet in the solar system most similar to Earth (e.g., Read and Lewis 2004; Read et al. 2015). With roughly half the radius of Earth (3396 km compared to 6371 km), Mars has around the same land surface area as Earth. Its tenuous atmosphere is composed mostly of CO_2 (95% by mass) plus much smaller amounts of N_2 (1.9%), Ar (1.9%), O_2 (0.15%), CO, H_2O, and other trace gases (Mahaffy et al. 2013) with a mean surface pressure of 6.1 hPa. It orbits at a distance of 1.4–1.6 AU[1] from the sun, receiving around half the solar irradiance of Earth (with significant annual variations) and with an orbital period of 687 Earth days. Mars rotates about its axis with a period scarcely different from Earth ($24^h\ 40^m$) and with an obliquity of 25°, resulting in a seasonal pattern of solar forcing that is remarkably Earth-like (although the seasons are longer in duration). It also sustains massive, permanent caps of water ice which are comparable in mass to Earth's Greenland ice sheet. Winter temperatures fall so low (−128°C, at the surface) that CO_2 also freezes, falling from clouds as snow or condensing directly onto the surface as frost, with up to one third of the total atmospheric mass deposited on the winter pole.

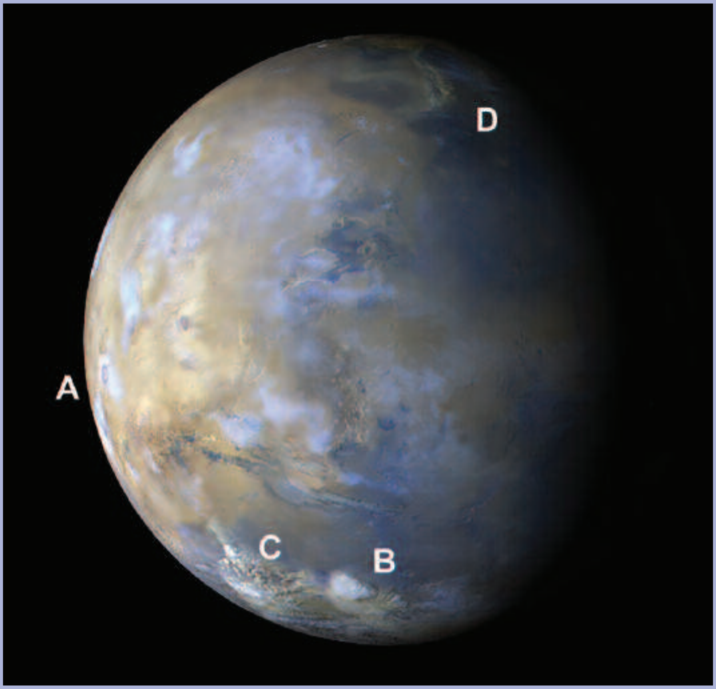

Fig. SB2.1. Mars as seen in May 2016 by the MARCI instrument on board the *Mars Reconnaissance Orbiter* spacecraft. Blueish-white features at low and midlatitudes are afternoon water ice clouds, typically tied to high topography, for example, the Tharsis Ridge volcanoes (A). White patches at high southern latitudes show surface frosts and fogs (e.g., B). Regional dust storms appear yellow, for example, lower left of center close to the southern cap (C), and the arc right of center at the top of the disc (D). (Image credit: NASA/JPL-Caltech/Malin Space Science Systems.)

Despite the low atmospheric density, Mars is meteorologically active with intense midlatitude/circumpolar baroclinic storms during autumn, winter, and spring, and frequent dust storms, especially during southern summer (when the planet is closest to the Sun at perihelion). Without surface oceans, this is essentially a desert planet with landscapes variously resembling arid sand and boulder fields or rugged mountain ranges found on Earth, although with numerous ancient impact craters and volcanic peaks. Hence seasonal variations in temperature in response to solar forcing are typically much larger than on Earth, and even the diurnal cycle leads to a strong atmospheric thermal tide that dominates the weather in the tropics.

Even though the present climate is cold, dry, and inhospitable, geological evidence indicates that Mars was more hospitable in the distant past (more than 3 Gyr ago), with features suggesting erosion by large volumes of flowing water, persistent lakes, or active glaciers, although the precise conditions are still controversial. But the existence of liquid water at the surface raises the possibility that Mars previously sustained life, so it has long been targeted for detailed exploration of its surface and climate, using both observations and model simulations.

Measuring and modeling the Martian atmosphere

In recent years a succession of sophisticated space missions have visited the planet, aimed at surveying and analyzing the Martian surface and atmosphere, both from orbit and using in situ surface landers. Since the late 1990s, starting with NASA's *Mars Global Surveyor* (*MGS*) spacecraft, Mars has been observed from circular polar orbit at relatively low altitude (350–450 km), enabling remote sensing of the thermal structure of the atmosphere via infrared spectrometry and the detection of clouds and

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[1] Where 1 AU is the mean Earth–Sun distance of 1.496 × 10^8 km; see http://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html.

aerosols of mineral dust, water, and CO_2 ice. The mapping configuration of *MGS* provided 12 sun-synchronous orbits per Martian day, sampling the full range of latitude and longitude across the planet every day (albeit fairly sparse in longitude), allowing the Thermal Emission Spectrometer (TES) instrument to recover profiles of temperature from the surface to altitudes of 40–50 km, together with column densities of dust and ice. This measurement density and consistency lends itself well to data assimilation approaches, given the availability of a suitable numerical models (e.g., Lewis et al. 2007; Hoffman et al. 2010). Such models borrow heavily from the techniques used for Earth and have now reached a level of sophistication that is beginning to rival Earth climate models, with complex radiative transfer parameterizations (including dust and ice clouds), hydrological cycles for both water and CO_2, dust transport cycles, dust storm evolution, and a range of surface processes (Forget et al. 1999; Newman et al. 2002; Steele et al. 2014).

Since the end of the *MGS* mission in 2004, a number of other spacecraft have continued to remotely sense the surface and atmosphere with increasing coverage and resolution, including NASA's *Mars Odyssey* and *Mars Reconnaissance Orbiter* (*MRO*), and ESA's *Mars Express* orbiter. The *MRO* in particular is equipped with the infrared limb-sounding instrument Mars Climate Sounder (McCleese et al. 2007), which can obtain vertical profiles of atmospheric temperature, dust, and ice opacity (Kleinböhl et al. 2009, 2011, 2017). This combination of instruments has thus extended the *MGS* record, so that the complete observational record stretches from 1999 to the present and consists of more than eight Mars years. Such a consistent record is transforming our view of the Martian climate, allowing detailed studies of dynamical processes across the planet and a clearer perspective on the interannual variability of Martian meteorology.

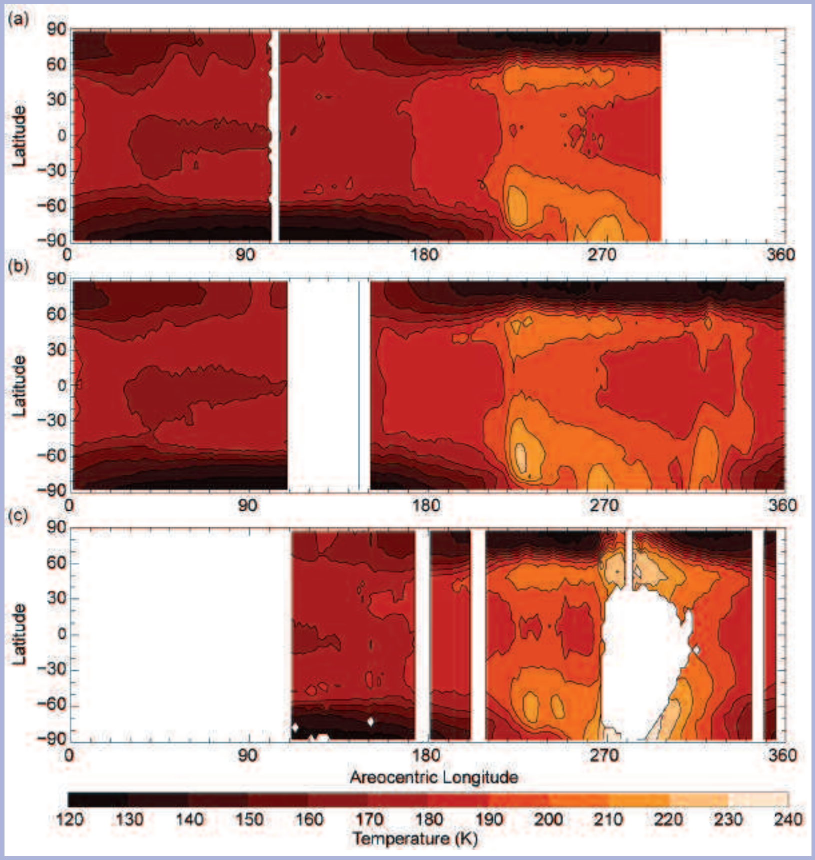

Fig. SB2.2. Zonally averaged temperature (K) on the 50-Pa surface as a function of time of year (LS) for (a) MY33 to Jan 2017, (b) MY32, and (c) MY28 from the start of the Mars Reconnaissance Orbiter mission; data from the MCS instrument. White indicates periods of missing data or when temperature retrievals on the surface were impossible owing to high levels of atmospheric dust.

The Martian climate in 2016–17

Figure SB2.1 shows a composite image of Mars, taken on 8 May 2016 (when Mars was farthest from the Sun; aphelion). The season is mid–late northern hemisphere summer on Mars [L_S = 149°, where areocentric longitude[2] is an angle that measures the seasonal date such that L_S=0° and 180° represent northern spring and autumn equinoxes while 90° and 270° represent summer and winter solstices]. Solar heating is significantly reduced near aphelion due to being farther from the Sun, and the atmosphere is typically colder and clearer than at other times of year. The regional dust storm, indicated by the arc-like feature (D in Fig. SB2.1), is dust revealing frontal-like behavior in a northern hemisphere weather system. Baroclinic cyclone waves, of similar horizontal scale to

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[2] The year on Mars starts at L_s = 0°, northern hemisphere vernal equinox (as the civil year once did on Earth).

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terrestrial weather (on the order of 1000 km), circulate around the northern mid-high latitudes (around 60°N) throughout autumn, winter, and spring (Lewis et al. 2016).

Figure SB2.2 shows how the zonal mean temperature retrieved on the 50-Pa pressure surface from the Mars Climate Sounder instrument aboard NASA *MRO* varied during the last two Mars years (MY) and during the first year of the mission, which featured a stronger, global dust event in northern winter. Following Clancy et al. (2000), MY are commonly numbered following a scheme where MY1 began on 11 April 1955; northern hemisphere winter of MY33 on Mars started 28 November 2016. Data from the day side of the MRO sun-synchronous orbit have been binned into 5° latitude and 2° L_S bins and averaged over all longitudes. The 50-Pa surface lies about 25 km above the reference datum on Mars, except during global dust events (e.g., MY28, L_S = 265°–300°), when it rises to about 30 km as the lower atmosphere warms and expands.

The most obvious features of the annual temperature cycle are the cold winter poles in both hemispheres. The first half of the year, northern hemisphere spring and summer, is typically cooler than the second half, as explained in connection with Fig. SB2.1. The notable warm patches at mid- to high southern latitudes from L_S = 220°–240° and L_S = 250°–290° are large dust events, denoted storms A and B following Kass et al. (2016). Neither approach global scales or are particularly strong in MY33; the warming at similar times at northern midlatitudes is the dynamical consequence of these dust storms, which enhance the strength of the single cross-equatorial Hadley cell, resulting in stronger adiabatic heating in the descending branch. So far, the Martian atmosphere in MY33 has appeared remarkably similar to the previous year on Mars (MY32; Fig. SB2.2b) with, if anything, even weaker dust storm activity. This is in direct contrast to some previous years, e.g., MY25 and MY28 (Fig. SB2.2c), which exhibited global dust events that warmed the atmosphere significantly (by up to 40 K) at these altitudes over a large range of latitudes and for intervals of at least 50 days.