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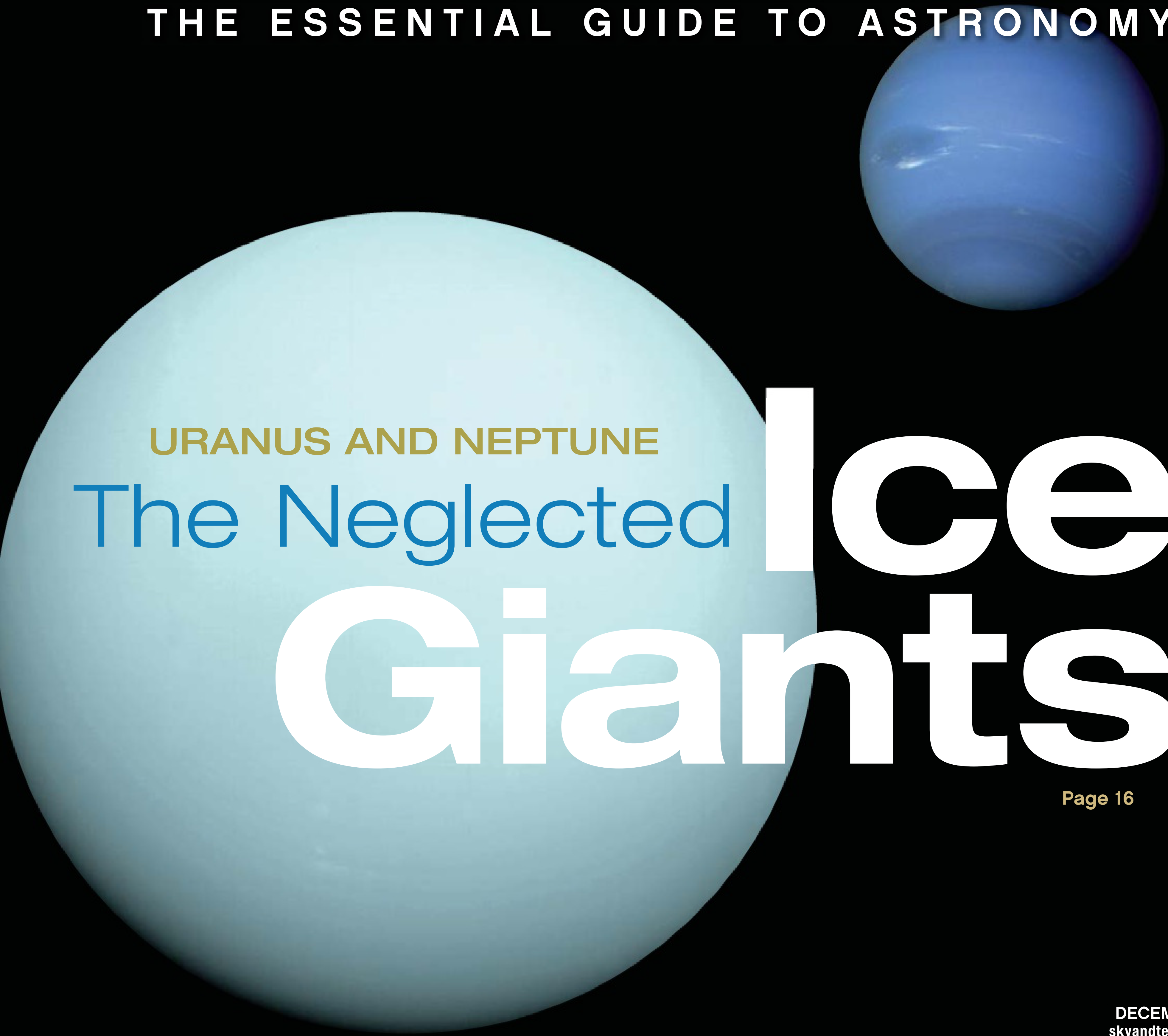
SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY



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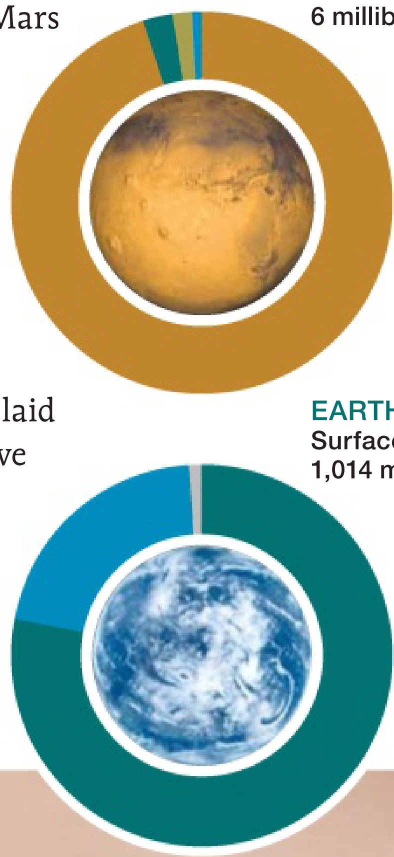
MARTIAN Weather Report

Storms, radiation, and dust combine to create a deadly environment on the Red Planet.

Over the past few decades, spectacular photos taken by landers and rovers from the surface of Mars have joined the ranks of the Space Age's most iconic images. One reason the photos have such appeal is because they paint a picture of an Earthlike environment. Rolling hills, layered mesas, fields of boulders, distant horizons, wispy clouds streaked across an endless, clear sky . . . the scenery could be out of a Western set somewhere in the desert of the U.S. Southwest. There is a familiarity to it, a timelessness evoked by geology laid bare, a sense of déjà vu — one feels like one may have driven through here before . . .

In reality, of course, nothing could be further from the truth. The "Earthiness" of Mars is a cruel illusion. While Mars is the most Earthlike planet in the solar system besides Earth itself,



MARS
Surface pressure:
6 millibars

EARTH
Surface pressure:
1,014 millibars

MAIN ATMOSPHERIC COMPONENTS

Carbon dioxide
Nitrogen
Argon
Oxygen
Other

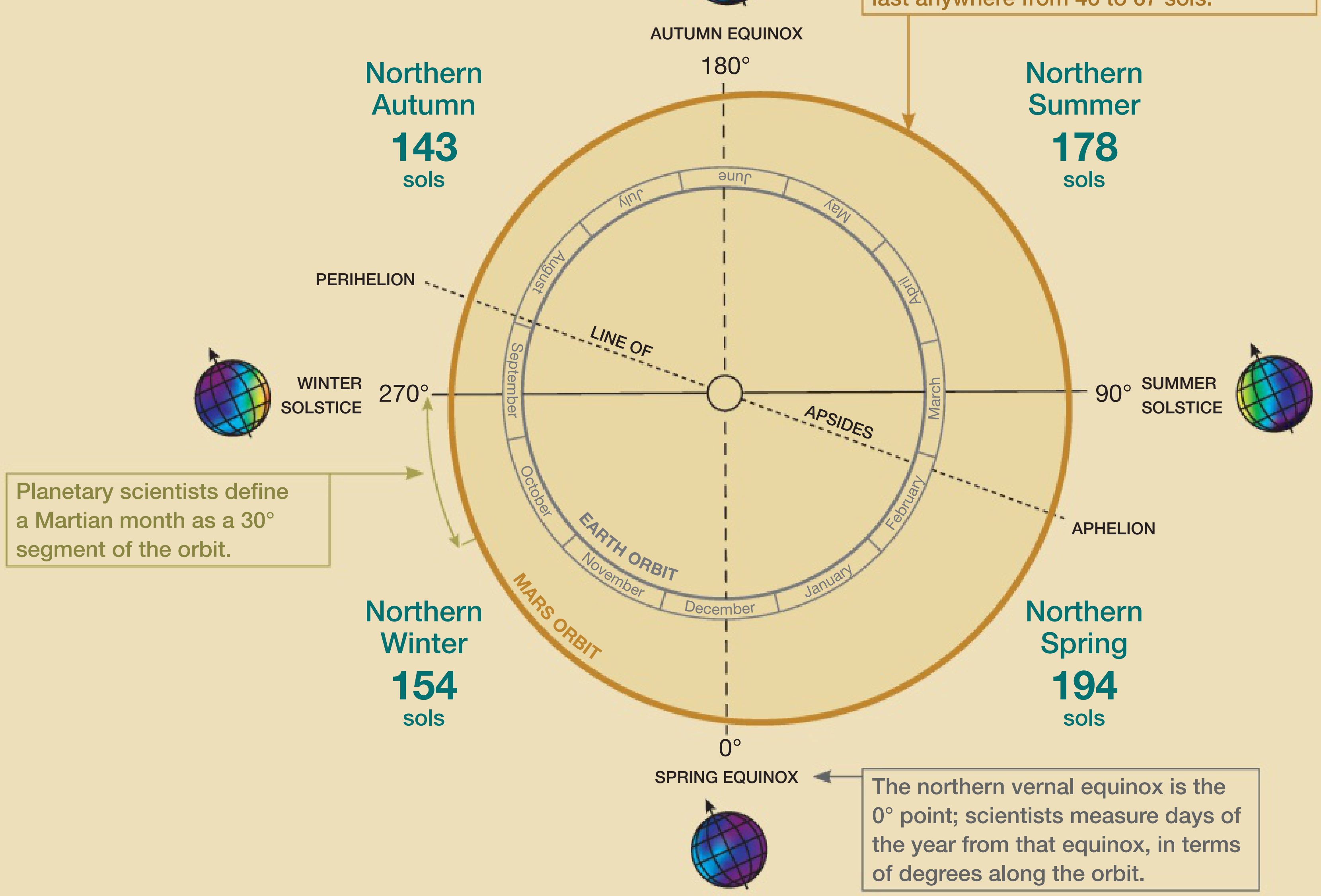
Planets not to scale

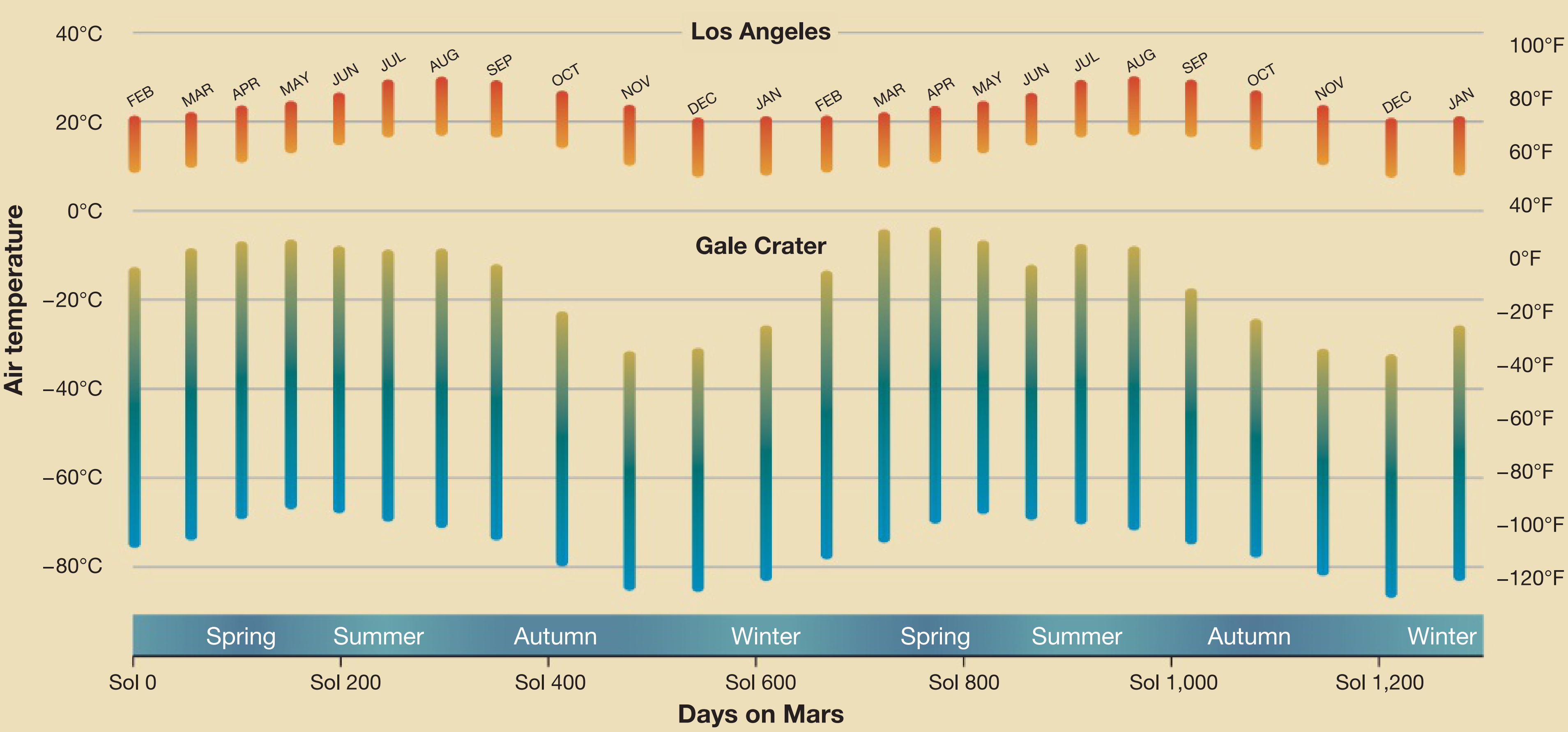
Unprotected on the surface, you would not only suffocate and get the mother of all sunburns, but you'd also freeze to death.

TWIN PEAKS Two modest-size hills sit about a kilometer away in this Mars Pathfinder composite. The colors are adjusted to approximate true color on Mars.

LANDSCAPE: NASA / JPL; GRAPHS: TERRI DUBÉ / S&T; EARTH: S&T ILLUSTRATION; MARS: NASA / GODDARD SPACE FLIGHT CENTER SCIENTIFIC VISUALIZATION STUDIO

MARTIAN SEASONS





▲ **BALMY OR BRRR** About two Martian years' worth of temperature data from the Curiosity rover's weather station show a clear seasonal pattern inside Gale Crater, which lies just south of the equator. Although the annual average temperature doesn't change much, daily conditions oscillate by about 60°C.

ORBIT AND SEASONS: GREGG DINDERMAN AND TERRI DUBÉ / *S&T*, SOURCES: J. D. BEISH / ALPO, MARS CLIMATE DATABASE; TEMPERATURE PATTERN: GREGG DINDERMAN / *S&T*, SOURCE: NASA / JPL-CALTECH / CAB (CSIC-INTA) the weather conditions on the surface are far from hospitable. From blistering cold to sky-darkening dust storms, Mars could kill you in so many ways.

Typical Martian Conditions

The Martian atmosphere is clear and dry, but it's thin, bearing down on the surface with only about 1% of Earth's surface pressure. In composition, it's 95% carbon dioxide (CO_2), which we can't breathe, with traces of nitrogen and argon and only minuscule amounts of water vapor and oxygen. Most of that oxygen comes from the breakdown of CO_2 by harsh levels of ultraviolet solar radiation, which barrages the surface because the planet doesn't have a protective ozone layer like Earth does.

Mars is on average about 50% farther from the Sun than Earth is, so it shouldn't be surprising that the environment is colder. However, the nature and magnitude of the coldness would be stunning to even the heartiest Arctic dwellers on our planet. Near the peak of summer, near the equator, the surface temperature during the "heat of the day" can briefly go above freezing, perhaps to 5°C to 10°C (41°F to 50°F) or more in certain places. But during most other times of the year, conditions are much more frigid, averaging more like –25°C to –10°C in the daytime and dipping down below –100°C on many nights. And that's the temperature at your feet — as you raise your thermometer up off the surface only a meter or two, the midday temperature can drop by 20°C to 30°C. Cozy toes but frozen nose.

Just like on Earth, it's colder the closer you get to the poles, and if you go far enough north or south in the winter, it gets so cold that the CO_2 starts to snow out onto the surface, forming dry ice. There is no similar analogy on Earth, because the water vapor that turns to snow and falls to the ground here is just a tiny fraction of the gas in our atmosphere. For it to snow on Earth like it does on Mars, the temperatures would have to drop to around –200°C so that our primary atmospheric gas, nitrogen, started to snow out onto the surface. Brrrrr . . .

Unprotected on the surface, you would not only suffocate and get the mother of all sunburns, but you'd also freeze to death.

Funky Seasons

Planets have seasons because of the tilt of their rotational axes — their *obliquity* — relative to the plane of their orbit around the Sun. The tilt determines how directly sunlight hits a hemisphere — or, in the extreme case of Uranus, whether sunlight reaches the hemisphere at all (see page 16). Earth's obliquity of 23.5° results in the winter, spring, summer, and fall seasons familiar to people living in mid-latitudes, as well as the long summer days and long winter nights familiar to people living closer to the poles. Jupiter and Mercury have almost no obliquity, so those planets do not have appreciable seasons.

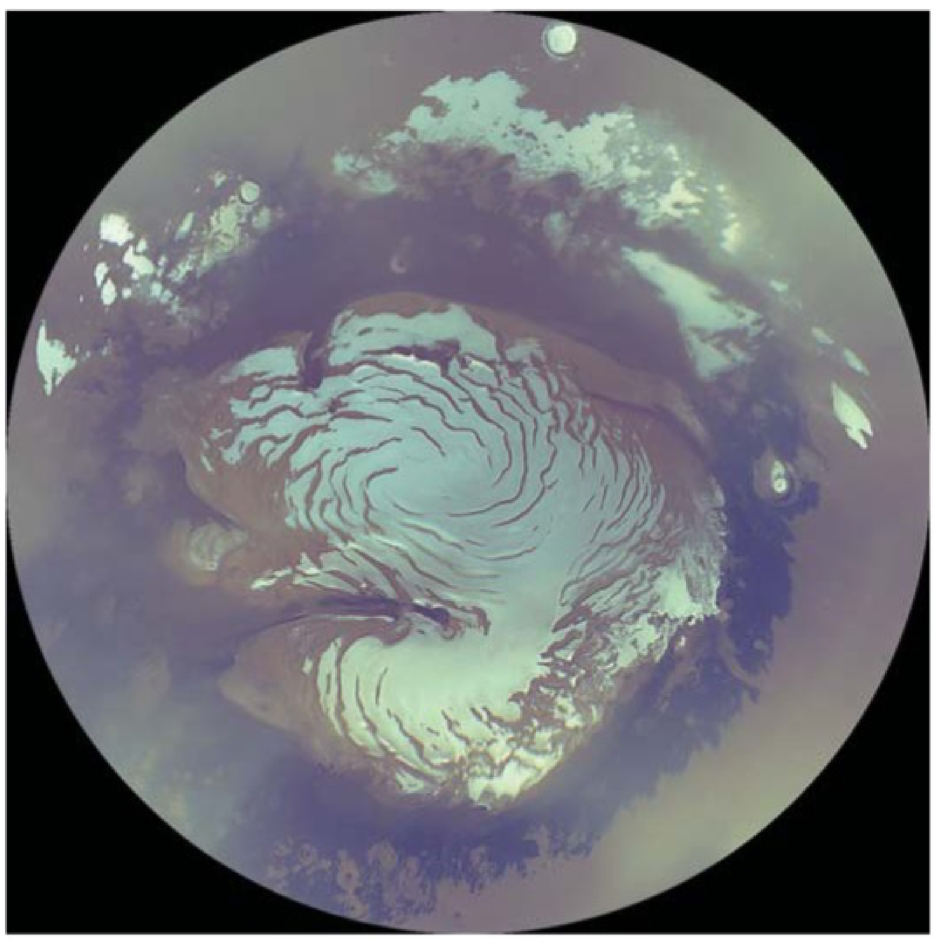
The obliquity of Mars (25.2°) is currently similar to that of Earth. Thus the planet has Earth-like seasons, though they're

Warmer temperatures provide more energy to fuel storms — both Earthlike systems dominated by thin water-ice clouds and distinctly Martian dust devils and dust storms.

approximately twice as long as our planet's because of Mars's greater distance from the Sun. The more direct sunlight in the summertime means warmer temperatures, which in turn provide more energy to fuel storms — both Earthlike systems dominated by thin, water-ice clouds and distinctly Martian dust devils and dust storms.

Complicating obliquity's effect, however, is Mars's *orbital eccentricity.* Its orbit is far more elongated than Earth's, which has a significant influence on the weather. Specifically, Mars's orbital eccentricity of 0.09 means that the planet's distance from the Sun changes from 1.38 astronomical units at perihelion (around southern summer/northern winter) to 1.67 a.u. at aphelion. That change in distance results in a whopping 45% increase in the amount of sunlight that the planet receives around perihelion compared to aphelion. In comparison, Earth's orbital eccentricity of just 0.017 results in only about a 7% change in the intensity of sunlight between January, when we're closest to the Sun, and July, when we're farthest. The Red Planet's more elongated orbit also means that the duration of southern summer is

▼ **POLAR CAP** This four-image mosaic from the Mars Reconnaissance Orbiter's MARCI camera shows the perennial north polar cap (white) atop layered material (light tan) and circumpolar dunes (dark brown).



NASA / JPL / MSSS

significantly shorter than the duration of southern winter: 154 Martian days versus 178, where a Martian day, or *sol*, lasts 24 hours and 39 minutes.

The large increase in solar energy input during southern spring and summer increases the average surface temperature, driving stronger daily winds, fueling more frequent storms, and helping to occasionally raise surface temperatures at latitudes near the equator above the freezing point of water. Conversely, the long polar nights during each hemisphere's winter season enable the surface temperatures to drop low enough (down to around –125°C) for up to about 1 meter (3 feet) of those famous CO_2 snow and ice deposits to accumulate. Sadly, the physics of dry ice and even water ice at Mars polar temperatures and pressures means that traditional skiing or sledding isn't possible; fans of such winter sports will have to find other pastimes, or invent new Mars-specific equipment technologies to feed their passions.

Uniquely Martian Storms

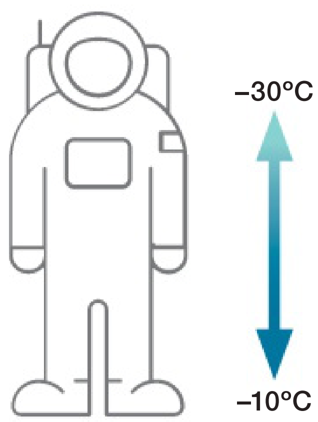
Just like on Earth, storms represent an important component of Martian weather on daily and seasonal time scales. Storms on Mars come in a range of sizes, from small house-size vortices comparable to terrestrial dust devils, to larger city-size moving walls of dust similar in some ways to terrestrial desert haboobs, to large-scale fronts that travel across major fractions of the surface, to fully planet-encircling systems that can dramatically affect the planet's surface and atmospheric temperatures. Scientists can monitor storms on all these scales using telescopes, orbiters, and surface landers and rovers. These instruments measure the way that the storms create and move clouds of both dust and water ice. They also help us study the way that movement of dust and sand can change the surface albedo over time.

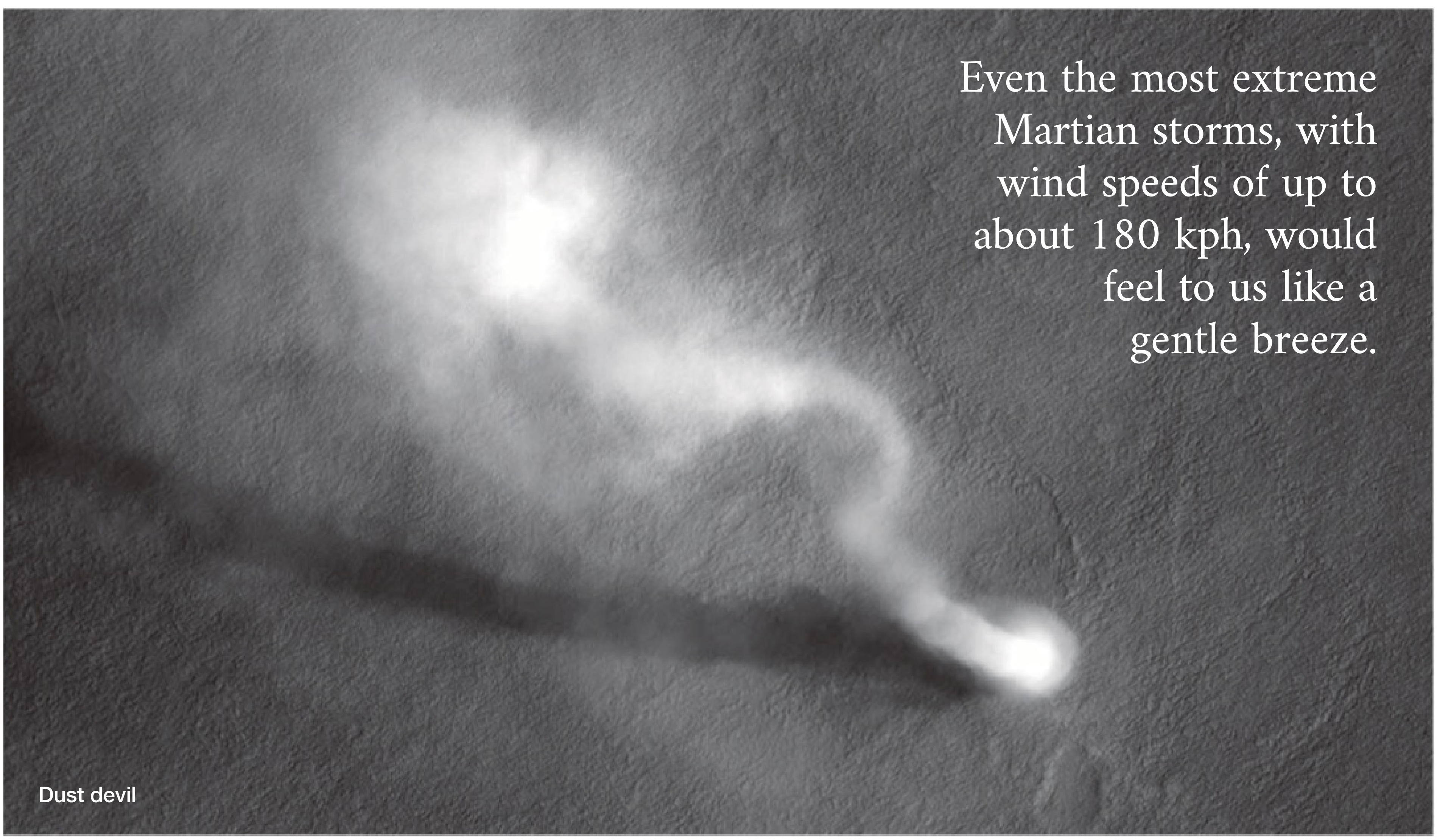
Despite some superficial similarities to terrestrial storms, however, Martian storms are significantly different from the kinds of storms that we are used to. For example, even though the planet's dust devils and dust storms can spin or move across the surface with hurricane-like wind speeds, the *force* exerted by those winds is extremely weak because the planet's atmosphere is so thin. Indeed, even the most extreme Martian storms, with wind speeds of up to about 180 kph (112 mph), would feel to us like a gentle breeze of around 21 kph (13 mph).

That might disappoint those of us who imagine our neighboring planet's tempests clobbering the surface like in the famous sandstorm scene early in the movie *The Martian*. Although the storm provided a dramatic introduction to the film's compelling "human vs. nature" theme, it's actually pure fiction. Rather than fighting intensely blowing sand and flying debris ripped off their habitats, astronauts like Matt Damon's character, Mark Watney, would instead have experienced something more like fast-moving feathers or dandelion seeds "pummeling" their

MIDDAY TEMPERATURES ON MARS

Astronauts' heads would be about 20° colder than their feet.





Dust devil

ASTRONAUT ICON: ARTEM KOVYAZIN / THE NOUN PROJECT; MID-DAY TEMPERATURES: TERRI DUBÉ / *S&T*; DUST DEVIL: NASA / JPL / MSSS spacesuits. That kind of meteorological reality would probably not have been as popular with Hollywood or moviegoers.

Time After Time

Nonetheless, even though the forces exerted by the winds are weak, they can have dramatic effects on the planet's weather, as well as on the surface itself. Martian storms are persistent and highly repeatable from sol to sol, season to season, year to year — and probably over the hundreds of millions to few billions of years that the planet's environmental conditions have been comparable to what they are today.

Scientists have been able to monitor the weather on Mars for centuries using Earth-based telescopic observations, but only in the past few decades has it become possible to observe weather patterns form, move, and evolve on Mars at a scale comparable to what we routinely get from terrestrial weather satellites. These stunning data sets, which now span nearly a dozen Martian years, come from the wide-angle color photos taken from orbit by the NASA Mars Global Surveyor mission's Mars Orbiter Camera (MOC; from 1997 through 2006), and then the Mars Reconnaissance Orbiter spacecraft's Mars Color Imager (MARCI; still active since 2006). MOC and MARCI researchers have created daily global maps of atmospheric storms and surface albedo changes nearly continuously for almost 8,000 sols — an unprecedented record that has finally laid bare numerous secrets about the weather on Mars.

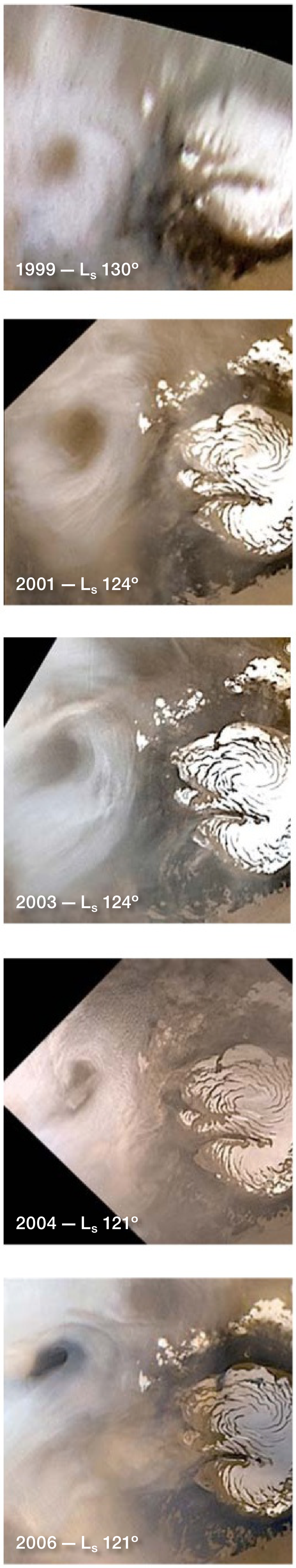
For example, time-lapse imaging over more than a Mars-decade has revealed that, as on Earth, there are specific *storm tracks* that fronts and weather systems take as they move across the planet. Among the most commonly traveled paths is a track that begins in the north polar region and extends southward along the dark region known as Acidalia Planitia, not far from the Mars Pathfinder landing site. Another storm track runs through the Utopia Planitia region, not far from the Viking 2 landing site. Several other common north-south paths have also been discovered. They all appear to be at least partly associated with winds intensified by two phenomena: temperature differences between bright polar ice caps and dark ice-free surface regions, and topographic differences between large low-lying basins and surrounding highland terrains. The paths taken by storms traveling south along these northern hemisphere tracks eventually cross the equator, where they begin to fan out and move in more east-west directions, partly because the terrain in the southern hemisphere is generally higher and more rugged compared to the northern one.

In general, the weather on Mars appears much more repeatable and much less chaotic than the weather on Earth. Remarkably, many of the same kinds of local storms occur in the same places and at the same times of year from Martian year to Martian year. For example, several times we've observed dust storms forming within the same part of the Valles Marineris canyon system at *almost precisely* the same time each year. Likewise, vortex-like storm systems of thin water-ice clouds peel off the north polar cap on nearly the same dates during each year's northern summer. This kind of repeatability is unprecedented on our planet — it would be like the same storm starting at exactly the same place on Earth on exactly the same day, every year.

Dust Storm Season

Another discovery from decades of weather satellite observations is that, for the smaller-scale storms, there really is no such thing as a general "dust storm season" on Mars. The concept was proposed in the mid-20th century based on Earth-based telescopic observations, which of course could only detect and monitor the largest storms on Mars, and then only for the part of the Martian year when the planet was closest to Earth. Monitoring the Martian weather up close, however, has revealed that there are dust storms on Mars essentially *every sol*. Some of them form from winds coming off the

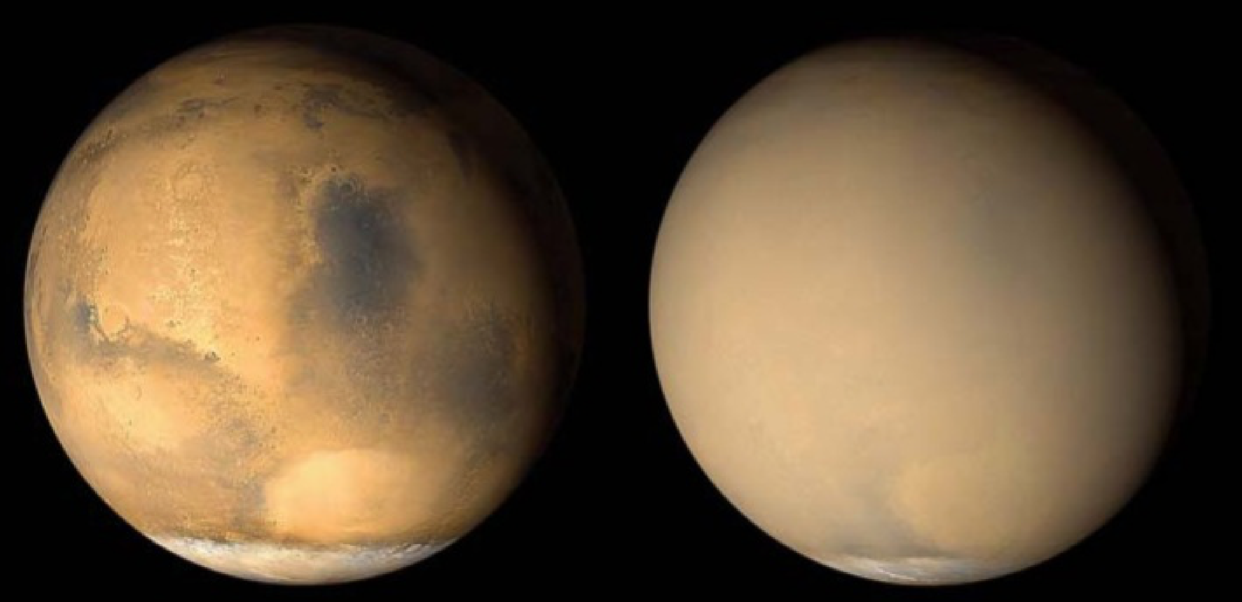
> As on Earth, there are specific "storm tracks" that fronts and weather systems take as they move across the planet.



▶ **DÉJÀ VU** In five successive northern summers, a water-ice cloud formed off the polar cap. The cloud appeared at about the same time of year (in solar longitude, L_s) and at the same location each year.

M. C. MALIN ET AL. / *MARS* 2010

The trigger for global dust storms on Mars is still a mystery.



GLOBAL STORM These images from the Mars Global Surveyor orbiter show a 2001 regional dust storm in the basin Hellas *(left, basin is bright oval feature)* that within a few days exploded across the planet, ultimately veiling the planet in dust *(right)*.

NASA / JPL / MSSS

polar caps and traveling along storm tracks, lifting dust as they brush across the surface. Others form more locally, as winds move across hills or canyons and become turbulent, or as warmer air rises out of craters or cooler air descends down mountain flanks.

The combined MOC and MARCI observational record shows that smaller dust storms frequently merge into larger regional storms. However, we still don't fully understand what occasionally causes them to merge into even larger hemispheric or truly global dust storms that shroud the surface from telescopic and orbital view and blot out the surface's view of the Sun.

Astronomers observed many such enormous storms in the 19th and 20th centuries; among the more recent ones are those in 1971 just before NASA's Mariner 9 spacecraft went into orbit, in 1977 during the Viking Lander missions, in 2001, and in 2007. The most recent global dust storm on Mars began in June 2018 and lasted for several months, turning daytime into night in the skies above NASA's solar-powered rover Opportunity and ultimately killing that robot after more than 14 years of successful operations on the Red Planet (*S&T:* Sept. 2019, p. 24).

As with the regional storms, the trigger for global dust storms on Mars is still a mystery. What we do know is that, unlike for smaller storms, there *is* a preferred season for the largest ones: Most occur during the "heat" of southern summer. The timing indicates that the increased energy of the southern summer's more intense sunlight fuels these enormous tempests. However, just like for hurricane season on Earth, there are also relatively chaotic local to regional effects from the atmosphere and surface that frustrate global dust storm forecasting. It's not yet possible to predict exactly how many large dust storms will occur each Martian year, or even whether a global-scale storm will occur at all.

On a smaller scale, the important weather factor that appears to initiate many of the dust storms on Mars is the *wind stress*, a drag exerted on the surface by the passing wind. If the wind stress is above a certain threshold, the wind can lift the tiny (smoke-size) grains of dust that cover the high albedo regions of the planet, keeping that dust airborne for weeks or even months at a time. In fact, the famous reddish sky of Mars photographed by landers and rovers is evidence that there is *always* some dust suspended in the Martian atmosphere. The oxidized iron in the dust grains absorbs most of the sunlight's blueish wavelengths and scatters its reddish ones, giving the Martian sky its distinctive tan hue. Indeed, if there were no dust in the atmosphere, the sky would be dark blue or perhaps even black (comparable to being on the Moon) because the atmosphere is so thin.

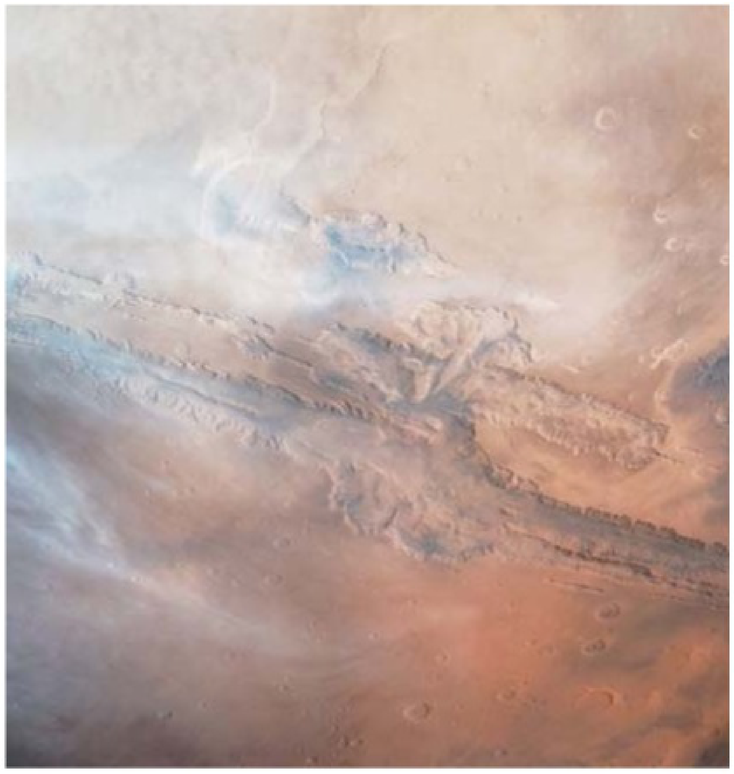
The airborne dust also gives Mars its distinctive blueish sunrises and sunsets. When the Sun is low in the sky, its light has to pass through much more of the atmosphere to reach a rover's cameras than it does at other times of day, and many more of the redder hues of sunlight are scattered away. Changes in the amount of dust in the Martian atmosphere determine how blue the sunrise or sunset is — an ironic and visually stunning contrast to the varying blushes of sunrise and sunset on our own planet. Dust is not only a key part of Mars's weather, it is a key part of Mars's character.

Long-Term Forecast

Just like on Earth, the distinction between *weather* (day-to-day environmental and meteorological phenomena) and *climate* (decades- or centuries-long weather trends) is crucial to understanding Mars. Surface, atmospheric, and satellite observations of the Red Planet are helping us to measure the sol-to-sol weather as well as to learn about long-term climate changes. Although Mars's climate is now far less volatile than Earth's, there is ample evidence in the geologic and atmospheric record that the planet's environment wasn't always the way it is today. Early Mars was much warmer and much wetter (*S&T:* July 2018, p. 14). Roughly 3½ billion years ago, this climate gave way to one influenced by widespread volcanism and episodic seas of water, then glaciers. Today's frozen desert is the result of this eons-long climatic evolution.

The evolution is currently at a standstill. The Martian climate will not change drastically in the near future — at least, not without help. Futurists have suggested that we might eventually be able to change the environment of the Red Planet by adding more heat-blanketing greenhouse gases to thicken its atmosphere, until the day-to-day weather and long-term climate match Earth-like conditions. However, such *terraforming* would take centuries to millennia, if not longer. Some researchers estimate that there is not enough CO_2 locked up in ice and rocks on Mars to even make it possible.

So if we want to send people to Mars in the much nearer future, we will have to find a way to live on the Red Planet the way it is, in all its stark, deadly beauty. The detailed understanding of Martian weather that is coming from recent and current robotic orbiters, landers, and rovers will become part of the common wisdom and daily reality of life for the first human settlers on the Red Planet. And perhaps they will be the ones who — spacesuited-up in layers to deal with the enormous daily swings in temperature, chipping away at the last of the long winter's dry ice, and battling (gentle) occasional dust storms — will uncover the deeper secrets still preserved on the Red Planet.



◀ **VALLES MARINERIS** The Viking 1 orbiter took this composite image of a cloudy afternoon over Valles Marineris, the largest canyon system in the solar system.

■ **JIM BELL** is an astronomer and planetary scientist at Arizona State University and the president of The Planetary Society. He has been a member of the Pathfinder, Spirit, Opportunity, and Curiosity Mars surface mission teams and leads the Mastcam-Z camera investigation for the upcoming Mars 2020 rover.

Keep up with the latest scientific results about Mars with the Red Planet Report: redplanet.asu.edu.

BLUE SUNSET The Mars Exploration Rover Spirit captured this sunset over the rim of Gusev Crater in 2005.

VALLES MARINERIS: NASA / JPL / USGS / JUSTIN COWART / CC BY 3.0; SUNSET: NASA / JPL / TEXAS A&M / CORNELL