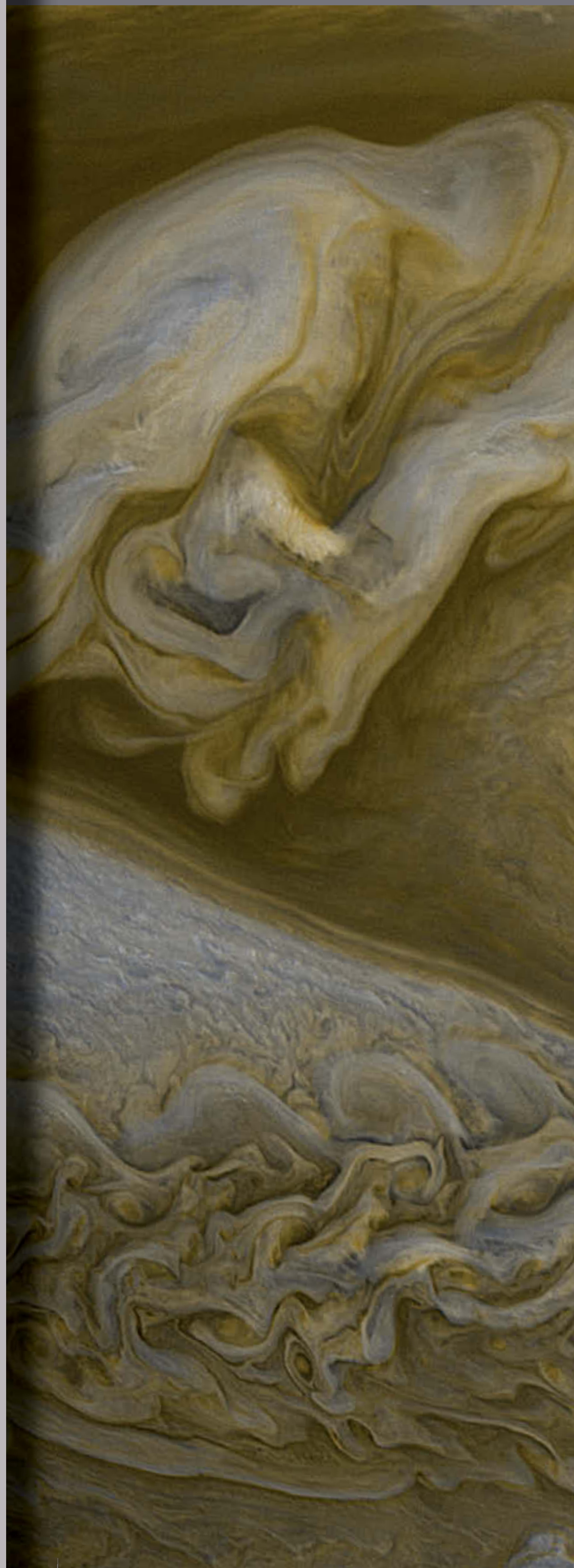
Nature's Wrath


The solar system's wild weather can make Earth's own extremes seem serene.

David Baker & Todd Ratcliff



"Can you believe this weather?"

It's more than just small talk. Weather significantly impacts our daily lives. Food, clothing, shelter, heating and cooling, work, play, transportation, communications, and health are all intimately affected by it. There is nothing superficial about the weather.

Earth's dynamic weather is ultimately the product of temperature gradients. A pleasant sea breeze at the beach is created by temperature differences between land and water. Refreshing rain showers can develop when unstable hot air rises up from the surface and cools, allowing the water in it to condense. Even on the global scale, energy imbalance between the equator and poles drives worldwide atmospheric circulation.

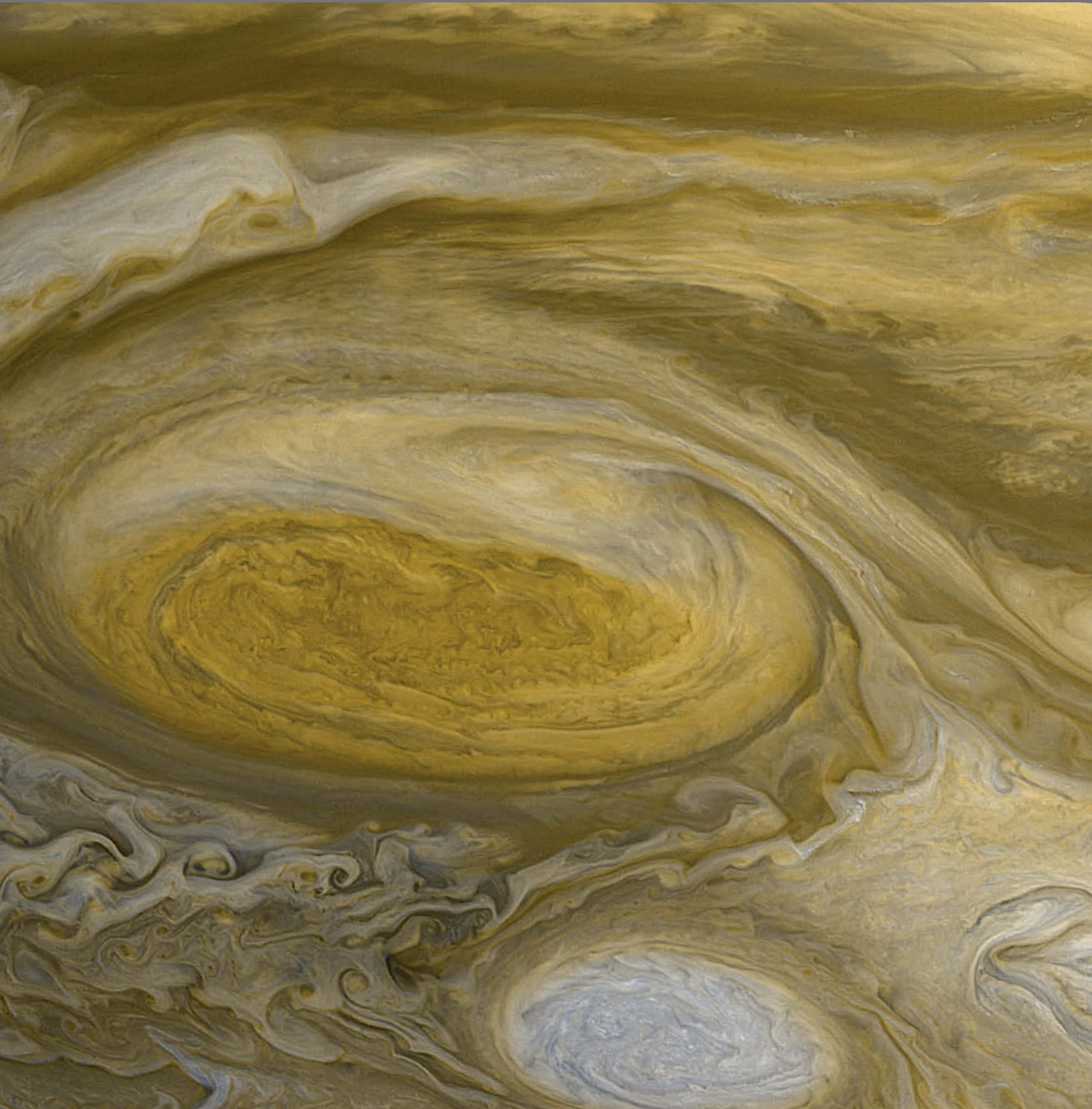
Yet Earth's attempt to equilibrate its temperatures doesn't always go smoothly. Violent twisters rip through Tornado Alley when warm, moist air from the Gulf of Mexico collides turbulently with cool, dry air from the north. Lightning sizzles at 28,000°C (50,000°F, nearly five times hotter than the Sun's surface) and damages more than $1 billion in property each year. Tropical cyclones such as Hurricane Katrina, with sustained peak winds of 78 meters per second (175 mph) and an ocean storm surge more than 10 meters (33 feet) high, ravage unprotected coastlines and damage delicate ecosystems.

Due to the chaotic nature of Earth's atmosphere, forecasting weather can be challenging. Small fluctuations in the atmosphere can lead to hefty weather changes later because of the complex ways wind, tempera-

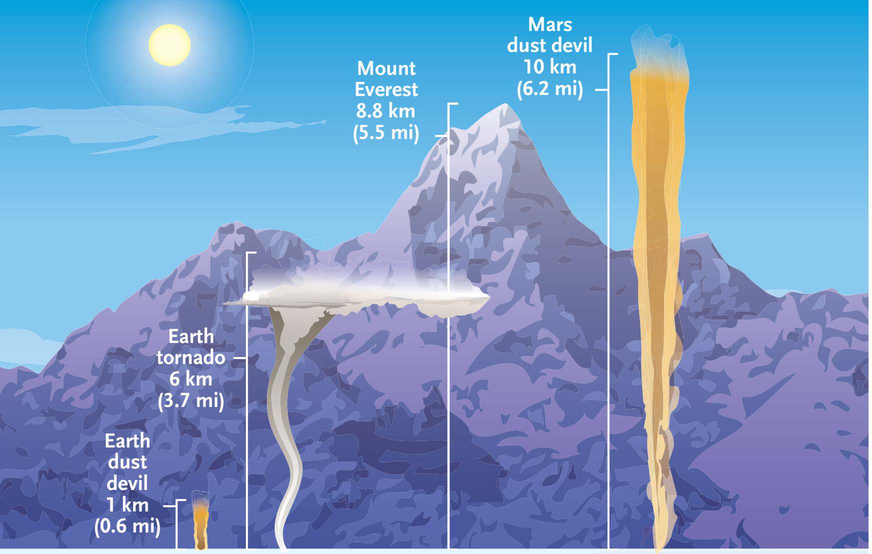
Left: Tracks left by dust devils' passage on Mars appear bluish in this color image from the Mars Reconnaissance Orbiter's HiRISE camera.

ALL IMAGES OF DUST DEVIL TRAILS: NASA / JPL / UNIVERSITY OF ARIZONA

This mosaic combines 24 images of Jupiter's Great Red Spot taken by the Voyager 1 spacecraft on March 4, 1979, when the spacecraft was 1.9 million kilometers (1.2 million miles) from Jupiter.



NASA / JPL, DIGITAL PROCESSING: BJÖRN JÓNSSON



S&T: LEAH TISCIONE

Martian dust devils can easily rise 10 km high, towering above similar vortices on Earth. Terrestrial tornadoes may extend 6 km into the sky, although that's something of a guess: what constitutes the top of a tornado isn't universally agreed upon, so height estimates vary.

A dust devil curves as a westerly breeze strikes it in this image from the HiRISE camera on NASA's Mars Reconnaissance Orbiter. Similar storms did more good than harm to the rovers, cleaning Spirit and Opportunity's solar panels of built-up dust.

Seen on March 14th this year by HiRISE, this gargantuan dust devil towered 20 km (12 miles) above the Martian surface as it swept across the northern region of Amazonis Planitia.

NASA / JPL-CALTECH / UNIV. OF ARIZONA (2)

ture, and moisture interact. Improvements in satellite observations and computer models now provide three-day forecasts with higher accuracy than the one-day forecasts of 1980, but some of the most severe weather can still only be predicted a few minutes in advance.

Weather on Earth certainly can be intense and capricious. But how does it compare with weather on other planets in our solar system? Is our weather truly extreme? The answers to these questions can make Earth's atmospheric tantrums look downright placid, and they might even have implications for the evolution of life throughout the solar system.

Vacuum Cleaners of Dusty Mars

Mars has long been known for its nasty weather. When Mariner 9 arrived at Mars in 1971, a global dust storm raged across the planet and obscured almost the entire surface. Only a handful of peaks rose above the clouds, including Olympus Mons, the highest mountain in the solar system at an elevation of 27 km (17 miles) above Mars's average radius. Fortunately for our space probes, these planet-wide storms are relatively rare. Only eight have been recorded since 1956, the most recent in 2007.

It's really the smaller dust storms that rule the Red Planet. Dust devils (or traces of them) appear almost everywhere on Mars, from the deep Hellas Basin to the lofty Tharsis volcanic region. The Mars Orbiter Camera (MOC) aboard NASA's Mars Global Surveyor spacecraft detected nearly 11,500 active dust devils over four Martian years. The Spirit rover observed 533 dust devils in Gusev Crater during one season alone.

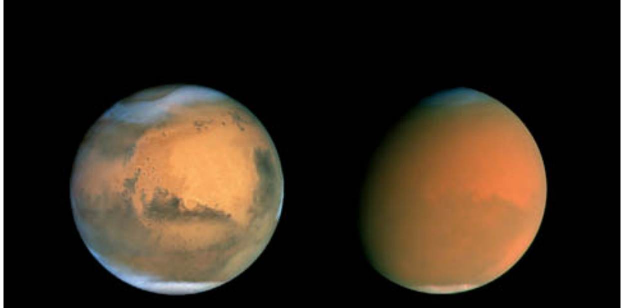
Shorter Martian vortices can be measured from lander images taken at the surface, but the tallest dust devils must be measured from above by orbiting spacecraft using shadow lengths and the angle of solar incidence. These observations show that "small" is a relative term: some dust devils can be more than a mile wide and reach higher than Mount Everest. Winds from these blowing behemoths travel the length of a football field in about a second.

Like tornadoes on Earth, these rotating giants leave their destructive mark on the Martian surface. As they sweep across the landscape, Mars's dust devils vacuum up a layer of red dust and expose the darker underlying substrate. Faster dust devils leave linear streaks, while slower vortices trace looping, curved paths. Dark tracks often remain visible for a month or longer, etching Mars with crisscrossed streaks.

But similarities between tornadoes and dust devils end with their signatures on the landscape. The fundamental

Watch roving Martian dust devils and hear lightning on Saturn at skypub.com/planetstorm.

The dust-devil-swept dunes near Mars's south pole look more like spun silk than a barren, alien landscape in this HiRISE image.



NASA / J. BELL (THEN OF CORNELL UNIV.) / M. WOLFF (SPACE SCI INST) / HUBBLE HERITAGE TEAM (STSCI / AURA)

Shown in natural color in these Hubble Space Telescope images, a global dust storm engulfed Mars in 2001 as the southern hemisphere's spring began. Only a few clouds appear in the left image, taken in June; by September, the storm had covered the planet for nearly two months.

dynamics of these whirling cousins are quite different. Tornadoes are strongly influenced by cold downdrafts that are enhanced by evaporative cooling behind the storm's core. These rear flank downdrafts wrap around the cyclone and squeeze rotating air into tighter rolls. In contrast, dust devils develop from a combination of warm updrafts and the uneven convergence of swirling horizontal winds (those pesky temperature gradients again).

Although tornadoes on Earth are relatively infrequent, Martian dust devils are remarkably commonplace. Based on the abundance of dark tracks on the Red Planet, many dust devils probably race across the barren surface every day. Yet because of the low atmospheric surface pressure on Mars, each dust devil individually packs a light punch — high winds but relatively small momentum. The winds are strong enough to lift dust particles (aided by the lower gravity of Mars, page 16), but an astronaut would barely feel them. Even a slight gust on Earth exerts more force.

The collective impact of these red whirling dervishes extends well beyond their local domain. Dust devils may contribute significantly to global atmospheric haze and the Martian dust cycle. Like clawing fingernails scraping away the skin of Mars, these incessant planetary vacuum cleaners are devilishly extreme.

Shocking Superbolts of Saturn

Bolts of lightning can be found sizzling throughout the solar system. All major planets with atmospheres (sorry, Mercury) show evidence of such electrical discharges. But nowhere does lightning crackle more powerfully than on the ringed giant Saturn.

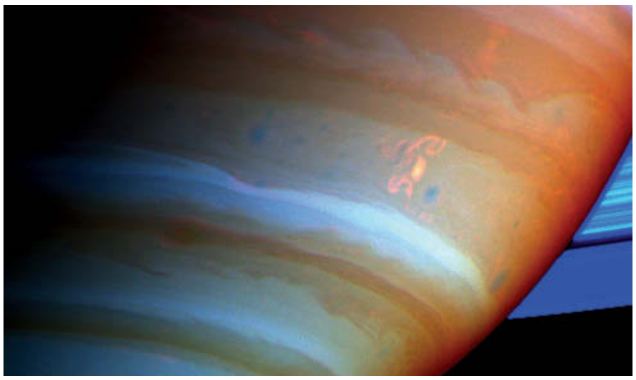
Remarkably for such a common phenomenon, scientists don't fully understand how lightning forms. The leading hypothesis involves collisions of ice particles within a thunderstorm. As hail and softer snow pellets fall through the clouds, these large ice projectiles scavenge electrons from smaller ice crystals. The lower clouds become negatively charged, while the upper clouds swell with positively charged ice crystals. When roughly 100 million volts build up in Earth's atmosphere, electrons discharge across the cloud (and sometimes to the ground) to paint dramatic displays of light and sound.

Because of water's electric dipole (the molecule is negatively charged on one side and positively charged on the other), water ice is particularly effective at stealing electrons. For this reason, planetary scientists usually focus on water clouds as the source of lightning. But these brilliant flashes of visible light are often hard to detect, especially on a planet's dayside or coming from water clouds buried deep within its atmosphere.

Luckily, lightning emits electromagnetic radiation at a variety of wavelengths. Radio waves in particular can travel great distances with minor attenuation. The ionosphere traps the low-frequency "whistler modes," named for their whistling sounds when heard over a radio receiver. Higher-frequency radio waves escape to space and sound like annoying static on an AM radio when intercepted by spacecraft instrumentation.

As NASA's Cassini spacecraft flew by Earth in 1999 for a gravitational assist on its way to Saturn, its Radio and Plasma Wave Science (RPWS) instrument detected radio bursts from lightning at a distance of 89,000 km above our home planet. The same instrument measured similar radio pulses at Saturn (called Saturn Electrostatic Discharges, or SEDs) much farther away, roughly 160 million km from the ringed planet. Since intensity drops off as the distance squared, Saturn's superbolts must be about a million times more energetic. Imagine for a moment what it must be like inside one of these superstorms — violent updrafts stronger than any on Earth, huge hailstones creating whopping charge separation, and epic lightning bolts perhaps as wide as the Washington Monument.

Until recently, most SEDs measured by Cassini originated from the southern hemisphere in a band at 35°



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The Dragon Storm, with bizarre arms in Saturn's "Storm Alley," released shockingly strong radio emissions in September 2004, a product of intense electrical activity within the storm.

These dust-devil-streaked dunes near Mars's Antoniadi Crater in Syrtis Major Planum resemble waves.

Superrotating Tropical Titan

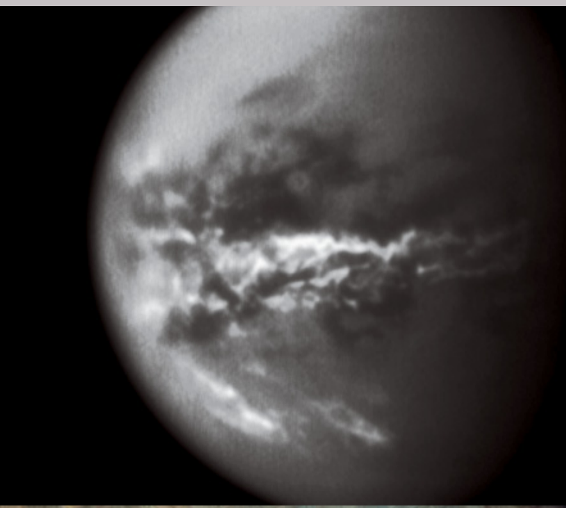
It may seem strange to call Saturn's largest moon "tropical." Titan receives only about 1% of the sunlight that reaches Earth, and its highest surface temperature is a bone-chilling –178°C (–288°F). But Titan's weather patterns closely resemble Earth's tropics and, perhaps even more so, those of blazing-hot Venus.

Titan is tidally locked to Saturn in a synchronous rotation of 15.9 days, meaning the same side of Titan always faces the ringed planet, just as the Moon always shows the same face to Earth. This relatively slow rotation makes Titan's atmosphere behave differently than the atmospheres of planetary bodies with short solar days. The dominant north-south circulation pattern on Titan consists of Hadley cells that extend from the latitude of maximum heating (e.g., the equator at equinox) all the way to the poles. For rapidly rotating planets, however, strong Coriolis forces prevent Hadley cells from reaching the poles. On Earth, Hadley cells only extend to ±30° latitude — a.k.a. the tropics.

Dynamic weather events at mid-latitudes on Earth, such as cyclonic low-pressure systems, undulating jet streams, and warm and cold fronts, are completely absent on Titan. Instead, the entire moon experiences weather characteristic of the terrestrial tropics (minus the hurricanes), including tranquil breezes and occasional methane showers.

But things are not calm everywhere on Titan. In the stratosphere, winds scream around the moon at over 100 meters per second (220 mph), rushing in the same direction as Titan rotates. Yet Titan's solid body only rotates at about 12 mps (26 mph). This prograde gusting means that Titan's atmosphere "superrotates," twirling completely around the moon in 1.9 days, roughly one-tenth the moon's synchronous rotation period. This extreme behavior is found on another slowly rotating body: Venus's atmosphere superrotates every 4 days compared to its solid-body rotation of 243 days.

The exact cause of superrotation on Titan and Venus remains unresolved. One leading hypothesis, supported by computer simulations, suggests that planet-scale atmospheric waves might transport significant amounts of momentum to the upper atmosphere, accelerating the winds to super-speeds.



Cassini took this image of Titan in 2010. The white band of methane clouds near the equator marks the current location of the intertropical convergence zone (ITCZ), the location where the southern and northern Hadley cells meet.

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south latitude called Storm Alley. As the season transitions to northern spring, even stronger superstorms are brewing in the northern hemisphere. A massive "white" storm develops roughly every 30 years when Saturn's north pole tips toward the Sun. These "Great White Spots" (May issue, page 20) have been observed only six times since first being detected in 1876. But, as the sixth storm's 10-year-early arrival proved, Saturn's weather isn't so easy to predict. SEDs from this superstorm (which evolved into a giant, turbulent snake completely encircling Saturn) were so frequent that Cassini's RPWS instrument sometimes could not even resolve individual lightning strokes in the cacophony. The most shocking developments are surely yet to come.

Jupiter's Permanent Storm

Devastating hurricanes may roil for weeks on Earth. Electrifying storms on Saturn may blaze for months. But for longevity, Jupiter's Great Red Spot takes the prize.

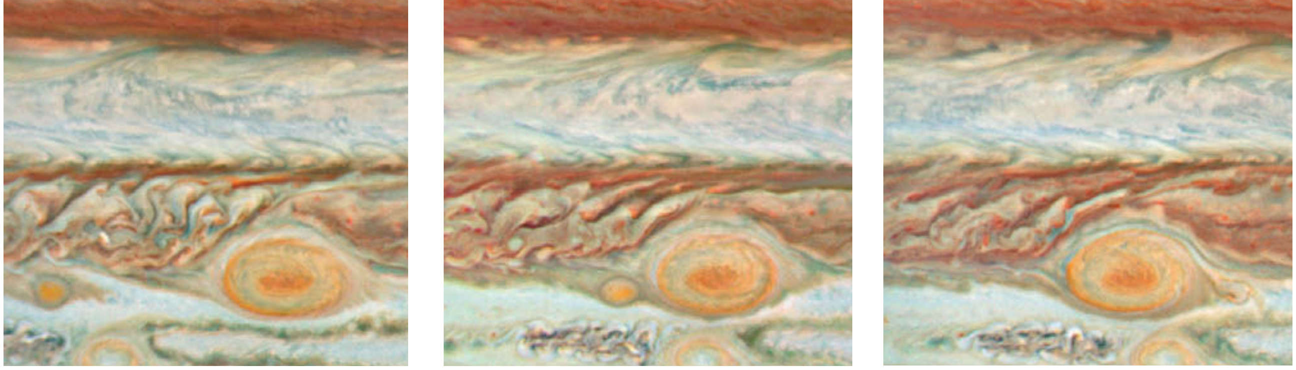
Italian-French scientist Jean Dominique (Giovanni Domenico) Cassini, whose namesake spacecraft is now orbiting Saturn, first definitively observed this "permanent" spot in Jupiter's southern hemisphere in 1665. (Robert Hooke is often credited with discovering the Great Red Spot in 1664, but Hooke's "small spot" possibly occurred in the northern hemisphere and could have been a shadow transit of a satellite.) Observing records are sparse for the 165 years following Cassini's death in 1712, but the giant storm has been systematically recorded since 1878. This makes the Great Red Spot at least 134 and possibly 347 years of age, and perhaps even older.

The exact reason for the 165-year gap in documentation may never be known. It's possible that the spot Cassini saw dissipated and a different storm (the one we see today) developed more than a century later. Or maybe the blemish simply faded in color — Hubble Space Telescope images show variations from deep red to light salmon in the span of just a few years — and it could not have been detected with the telescopes of the 18th and 19th centuries.

Regardless of its exact age, the Great Red Spot is imposing. The anticyclonic high-pressure system towers 8 km over the surrounding cloud tops (nearly as high as Mount Everest). Winds whip around the giant whirlpool at 190 mps (425 mph), faster than any winds ever recorded on our home planet. Almost three Earths could fit inside the unrelenting maelstrom.

Why has this giant vortex lived for so long? First, intense internal heating from gravitational contraction fuels Jupiter's turbulent weather. The cloud tops receive 70% more energy from the planet's interior than from the Sun. Powerful thunderstorms (many of which have been detected

HiRISE resolved features only 1.4 meters (55 inches) across when it snapped this image of the Martian surface.



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The Great Red Spot devours a smaller vortex in this sequence from 2008. Three red spots can be seen in these Hubble Space Telescope images: Great Red Spot, Little Red Spot (same latitude but to the west of the great one), and Red Spot Junior (south of the other two spots). In the last panel, the Little Red Spot (now on the east side) gets swallowed by its giant neighbor.

near the Great Red Spot) transport much of this heat from the deep interior to help equilibrate the energy imbalance.

Second, friction caused by land masses on Earth destroys hurricanes when they hit shore, limiting their lifetimes to a few weeks at most. Without a solid surface, Jupiter's interior exerts much less drag on the atmosphere. The end result is that Jovian storms can churn for years.

But the Great Red Spot isn't your typical low-friction Jovian storm. This vicious anticyclone is trapped between two high-speed jet streams, a westward jet to the north and an eastward jet to the south. Computer simulations show that multiple vortices, not just one, develop at the interface of such strong opposing jets. These vortices eventually consolidate into one big stable vortex. In other words, the Great Red Spot eats smaller spots to maintain its impressive physique.

Similar spots have been detected on the other giant planets — white spots on Saturn, white spots on Uranus (see page 54), and the Great Dark Spot on Neptune — but none of them seems to have the stamina of the Great Red Spot. Why such a long-lived vortex only on Jupiter? It's an intriguing puzzle, especially considering that Saturn also has strong internal heating and wicked jet streams.

Launched in August 2011 and set to arrive at Jupiter in 2016, NASA's Juno spacecraft will investigate the composition, structure, and dynamics of the Jovian atmosphere (*S&T:* September 2011 issue, page 18). A six-band microwave radiometer will penetrate the cloud tops to examine the deep atmosphere down to the 200-bar pressure level (about 400 km below the ammonia clouds). An infrared spectrometer will map deep water clouds and thunderstorm development. This important new mission may finally reveal the secrets of Jupiter's eternal storm.

Nature's Wrath or Nature's Nurture?

Mars, Saturn, and Jupiter all exhibit weather beyond the norm, with armadas of colossal dust devils, superbolts of shocking proportions, and a raging red tempest that may never die. For successful space exploration, *in situ* spacecraft must be built to investigate and withstand these types of extreme weather.

Weather is a critical consideration when designing space missions. Scientists pored over images for evidence of dangerous dust devils when choosing the landing site near the north pole for NASA's 2008 Phoenix Mars Lander. Lightning on Saturn poses huge risks for electronics on future atmospheric probes, and the never-ending roller coaster ride of the Great Red Spot probably would shred a typical weather balloon. Human exploration in these violent conditions is almost unthinkable.

Brutal weather on other planets may make it difficult for any life form (as we know it) to survive. Consider a hypothetical microbe trying to get a flagellum-hold on Mars. Just when it gets attached to a nice piece of dust with some water ice nearby, *whoosh!* a dust devil mercilessly relocates it to a fatal locale. Nature's wrath may not be a microbe's friend.

On the other hand, extreme weather might encourage life. Hurricanes rejuvenate coral reefs, bring precipitation to drought-stricken areas, and flush out toxic pollutants from estuaries. Lightning in Earth's early atmosphere might even have sparked life by creating organic compounds such as amino acids. Maybe abnormal weather on other planets could prime their environments for life. We won't know until we look.

In terms of absolute wind speeds, vortex size, or electrical power, Earth may not have the wildest weather in our solar system. But for supporting life, there is nothing third-rate about the Third Rock. Earth's weather might just be the perfect storm. How wild is that? ✦

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On Mars, even fields of sand dunes built up inside craters bear the mark of passing dust devils.