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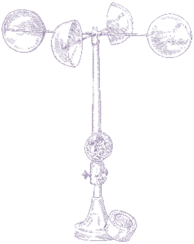

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this means that as it passes through the surface of a falling raindrop, it is deflected (refracted) to a different degree. After entering the raindrop, some of the light is then reflected from the back surface of the drop to re-emerge through the front, where it undergoes a second refraction. So, if you stand with your back to the Sun and face the rain, you see the rainbow of colors.

RAINBOW ANGLES

The angle of the rainbow is always the same and is close to 42 degrees. The reason the rainbow is an arc is simply that the ground gets in the way, so if you are lucky enough to spot a rainbow while flying at altitude you can sometimes make out the whole circle. In very bright examples of rainbows, it is also sometimes possible to make out a fainter but discernible second bow, concentric but outside the main bow. This is caused by light that undergoes two reflections in the raindrops and the colors switch order compared to the first bow.

WAVELENGTH AND COLOR

Splitting the white light from the Sun into its component colors produces a spectrum that ranges from red, which has the longest wavelength, to violet with the shortest wavelength. It is the shorter wavelengths that are refracted most as the light enters and leaves the raindrop, and this is why violet is on the inside of the rainbow and red is on the outside.

← Rainbows result from the refraction of sunlight by raindrops, so you need simultaneous sunshine and rain to see a rainbow. Multiple bows like the one shown here correspond to multiple reflections of the light inside each water droplet.

HAIL

Hailstones are not stones at all of course, but compact, hard balls of ice that have accreted onto a small nucleus while being suspended high in the atmosphere before falling out and reaching the surface. If you slice a good-size hailstone in half, you can see the rings, much like tree rings, where layer after layer of ice has accreted onto the hailstone.

GLOBAL HOTSPOTS

Hailstorms can be very costly events and are one of the weather hazards that do the most damage to crops and property. The Australian hailstorm of April 1999 cost billions of dollars and was one of the costliest weather events in recent Australian history. Understandably, insurers are keen to know where the hotspots for hailstorms are around the world, but this is not always easy to map out because hailstorms can be isolated, small-scale events that often go unobserved. Nevertheless, we know of a number of hotspots for hailstorms. The mid-United States holds the record

HAILSTONE SUSPENSION

The conditions needed to produce a really intense hailstorm include lots of surface warmth, which leads to lots of rising motion, and lots of wind shear—the change in winds with height—which helps to spin up the storm. Intense rising motions are needed to support the hailstones in mid-air: a 1-cm (1/2-in) stone needs the air to be rising around 10 m (30 ft) every second to be supported, and this increases with the size of the hailstone. Keeping the hailstones above the melting level for long enough to grow is important because the formation of large hailstones requires the capture of as much freezing water and other hailstones as possible.

← Hailstones form as water accretes onto a central nucleus. As the hailstone enters different environments within the cloud, it accretes different-sized particles of water and ice, creating layers like those found in an onion.

for the most frequent hailstorms, where localities have 20 days of hail in a typical year, but there are also other hail hotspots in equatorial Africa, Southeast Asia, Argentina, southern Africa, and the Mediterranean.

GIANT HAILSTONES

Hail is usually around 5 mm (1/4 in) in diameter and small hail often melts as it falls, descending below the melting level into the warmer atmosphere below and turning back into rain. However, the biggest hailstones can be bigger than your fist and pack a massive punch as they hurtle to the surface because for every doubling in size of the hailstone its energy goes up by 16 times!

FUTURE HAILSTORMS

What will happen to hailstorms in the future as the climate warms? Will the warmer atmosphere melt hailstones so that they become less frequent? Or will hailstorms become more intense and cause more damage? The answer to this question is still debated and there are competing effects, but it seems that the extra warmth near the surface means that small hailstones will be less common as they will more likely melt. However, the warmth will also give rise to more intense rising motion and hailstorms, and the raising of the melting level due to the warming of the air in the lower atmosphere means that only the large hailstones will survive to the surface before melting. Overall, this means we can probably expect record-breaking hailstones in future.

SNOW

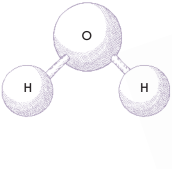
Snow is the remarkable sub-zero alternative to rain if there's enough moisture around. Snowflakes are made of water crystals and most are a conglomerate of different individual crystals. There is lots of air in snow and little water, so 10 cm (4 in) of snow on the ground corresponds to just 1 cm (1/2 in) of rain.

6-FOLD SYMMETRY

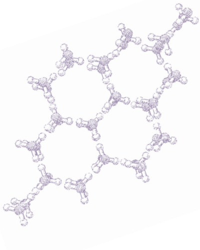
Why do all snowflakes have six points? Water molecules have two hydrogen atoms and one oxygen atom in a V-shape with an angle of 105 degrees. This isn't too far from 120 degrees, so, as water molecules freeze, they produce regular hexagons, but it's impossible to predict the shape of a snowflake in advance because new molecules joining the crystal are affected by the slightest change.

Some of the deepest snowfalls in the world are found in Japan, where 30 ft (10 m) of snow is common during winter northerlies. So perhaps it is no coincidence that 20th-century Japanese researcher Ukichiro Nakaya was the first to show that snowflakes always come as plates or columns, depending on humidity and temperature.

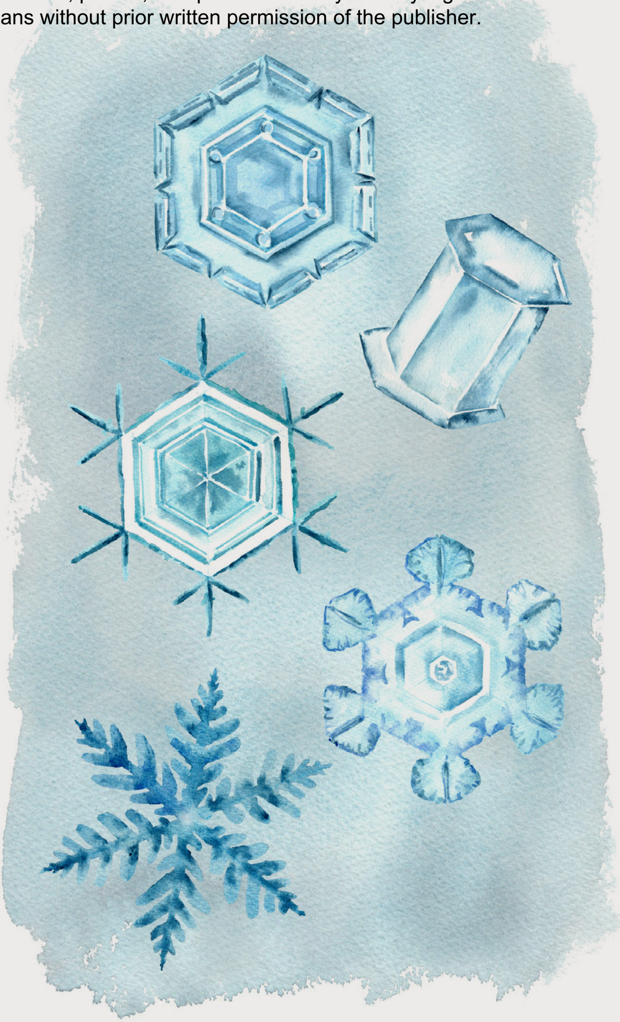
↓ Water molecules have a bent structure with the two hydrogen atoms of H_2O forming an angle of 104.5 degrees.



↓ Water molecules bond in hexagonal, repeating structures, which have 120-degree bond angles.



→ Microscopic 6-fold symmetry is expressed in the macroscopic shapes of snow and ice crystals. An infinite variety of shapes is possible and the exact type depends on details of the ambient temperature, pressure, and humidity.



THUNDER AND LIGHTNING

Lightning is an electrical discharge that occurs between thunderstorms and the ground or, more commonly, within clouds. The lightning "bolt" is a gigantic spark that allows an electric current to flow and releases large amounts of heat and light. The air gets so hot during lightning that it expands faster than the speed of sound, and this creates a shock wave that travels through the atmosphere as the booming sound we call thunder.

The flash of lightning and boom of thunder also give rise to the common method of determining how far away a thunderstorm is. Compared to the sound, the light travels almost instantaneously, so the light arrives at your eye almost straightaway, while thunder arrives after the sound has had time to travel. The speed of sound is around 300 m/s (300 yards per second), so if you count the seconds between flash and boom and multiply by 300, you get the distance to the storm, and if the time gets shorter each time, then the storm really is getting closer.

ELECTRIC CHARGE

We still don't understand all of the microscopic processes at work in a thunderstorm but rapid rising motion causes friction and collisions between lighter ice crystals and heavier falling graupel (granular pellets). This rubs off electrons onto the graupel, leaving the positively charged ice crystals to rise to the top. A few hours later, the charge difference between the positive cloud top and its negative base can result in a voltage difference within the cloud (or with the ground) of many millions of volts. Such high voltage differences can lead to electrical breakdown and a sudden drop in resistance as electrons flow through narrow forked channels called leaders, rushing to the Earth in a tiny fraction of a second as lightning strikes.

LEADERS AND STREAMERS

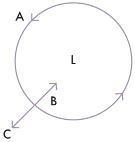
As a thunderstorm passes overhead, the negatively charged cloud base repels electrons in the atoms at ground level and the surface becomes positively charged. If the effects are strong enough, positive charges start to make the air glow and flow upward in a streamer as they try to connect with the negative leaders coming down from the cloud base. These upward streamers are most often seen reaching out from high points like tall buildings just before a strike.

↓ Lightning is a gigantic spark that resets the slow buildup of electrical energy when the voltage difference is enough to overcome atmospheric air resistance. Thunder results from the supersonic velocity of the heated air.

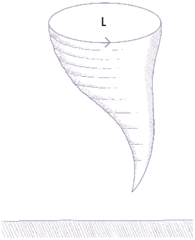
TORNADOES

Usually a few hundred meters in diameter, tornadoes are among the smallest extreme weather systems. Tornadoes are cyclones and have low pressure at the center, but unlike hurricanes or midlatitude windstorms, the Coriolis force is negligible in these small vortices. Instead, the push of the air toward the low pressure in the tornado is balanced by the centrifugal force due to its rapid rotation. The Fujita scale is used to measure tornado strength: the strongest category (F5) tornadoes have winds over 415 km/h (260 mph).

Tornadoes can travel a few miles before they "rope out," narrowing and twisting as they break apart. They're small compared to the resolution of typical weather forecasts, so meteorologists concentrate on predicting the strongly convecting, sheared wind regions that provide good spawning grounds for tornadoes. Tornado alley in the mid-United States is famous, but they are found in many regions of the world—when they form over the ocean they are known as waterspouts.



↙ Forces in a tornado. The pressure gradient force inward (B) is balanced by centrifugal force outward (C). This results in fast cyclostrophic winds (A) in small-scale, rapidly rotating vortices such as tornadoes.



↙ The low pressure inside a funnel cloud (L) causes the water vapor in the air inside to condense, which is why we see the funnel. It only becomes a tornado if the funnel reaches the ground.

→ Tornadoes are small but devastating columns of rapidly rotating air that form at the base of cumulonimbus clouds in severe convective storms. A single storm can produce multiple tornadoes and a typical tornado will wreak havoc along a path of a few miles. Tornadoes almost always rotate cyclonically despite the negligible effects of the Coriolis force on their small scale since they take their spin from the parent storm.

HURRICANES AND TYPHOONS

Hurricanes and typhoons are the classic spiral storms you see in satellite photos of the Earth from space. Hurricanes and typhoons are actually the same phenomenon, it's just that typhoon is the name for a Pacific storm and hurricane is the name for an Atlantic storm—they are both examples of tropical cyclones.

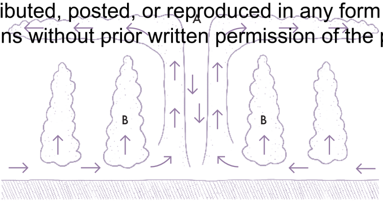
FORMATION

Hurricanes and typhoons form over the warm waters of the tropical Atlantic and the tropical Pacific. However, they need to feel the Earth's rotation and so they can't form right on the Equator. Instead, they usually develop between 5 and 20 degrees North. The storms develop from smaller convective weather systems; in the Atlantic case, these are often associated with wavelike disturbances traveling westward off the African continent.

Developing hurricanes and typhoons travel westward in the trade winds and strengthen as they extract energy from the warm ocean surface. Air spirals in toward the center of the storm near the surface and outward at the top of the storm. Intense convection forms in

CONDITIONS FOR TROPICAL CYCLONES

Hurricanes and typhoons only form when the sea surface is warm enough and typically above 26°C (79°F). They also require weak wind shear between the easterly trade winds near the surface and the westerly winds aloft. If these are too strong, they can shear out and disrupt the storm, preventing it growing. There are year-to-year changes that make some years active and some years weak for tropical cyclones. For example, although it delivers extreme weather in other forms across the globe, El Niño (see Chapter 5, page 60) tends to increase the wind shear in the Atlantic and reduce the intensity and number of hurricanes.



← The air flows into a hurricane near the surface, carrying warm moist air to power the storm. Cloud bands (B) spiral around the central eye (A) where descending air creates clear skies and a lull in the wind.

bands around the storm center and the condensation of moisture aloft acts like a heat engine, adding heat to the air and powering it toward ever-stronger winds.

All tropical cyclones have low pressure in the center and rotate counterclockwise in the Northern Hemisphere. Southern Hemisphere storms are less common and rotate clockwise. In a mature storm, a small region of descending air forms in the center. As the air descends, it is compressed and warms, so there is no condensation, cloud, or rainfall here and this eye of the storm is clear and quiescent. It is surrounded by a towering ring of deep storm clouds known as the eye wall, where some of the strongest winds (up to 320 km/h/200 mph) are found.

TROPICAL CYCLONE DISASTERS

Typhoons and hurricanes are the most energetic and dangerous storms on the planet. Typhoon Haiyan (aka Yolanda) tracked westward in the Pacific, growing to the highest category we have for tropical storms—Category 5 on the Saffir–Simpson scale—with the strongest winds ever observed in a tropical cyclone to that date. Haiyan made landfall in the West Pacific in early November 2013, where it devastated large areas of Southeast Asia. The Phillipines was among the worst countries affected and more than 6,000 people were killed by Haiyan.

Hurricane Katrina in August 2005 was the worst Atlantic hurricane disaster in modern times. It entered the Gulf of Mexico, where it was boosted by warm waters and made landfall over Louisiana and Mississippi. Heavy rainfall combined with a massive storm surge almost 10 m (30 ft) high flooded New Orleans for many weeks and Katrina claimed almost 2,000 lives.

EXTREME RAINFALL AND FLOODS

Inland flooding can have many exacerbating factors, ranging from changes in land use to changes in river courses, but the one driver that almost all inland flooding events have in common is extreme rainfall.

UNITED KINGDOM, 2007

Floods occur around the world and, in summer 2007, the Atlantic jet stream meandered southward of its usual position, bringing a persistent series of slow-moving cyclonic weather systems that hit northwest Europe and lingered over the United Kingdom. Much of England was affected and some regions received a month of rainfall in a single day, causing a whole series of floods. Towns were inundated with water and the iconic image of Tewkesbury Abbey, in Gloucestershire, under water for the first time in over two centuries, covered the front pages of newspapers. Hundreds of thousands were left without drinking water and flooding was also widespread in Wales and Scotland. These floods prompted a government review and new policies to tackle future flooding in the UK.

PAKISTAN, 2022

It had been some years since the summer of 2010, when Pakistan had last experienced really extreme prolonged summer rainfall, but in 2022 the summer rainfall record was set to be broken. A supercharged monsoon season, exacerbated by La Niña conditions (see Chapter 5, page 60) in the neighboring Pacific and climate change, sent low pressure systems extending west into Pakistan and excessive summer monsoon rains. The country received nearly three times its normal summer rainfall and the extra rainfall inundating Pakistan was more than five times the increase seen in a usual wet summer. After the Indus River burst its banks, more than 10 percent of the country was flooded, with millions left homeless and nearly 2,000 lives lost. The impacts of this devastating flood, the worst in many decades, were costly and longlasting.

COASTAL FLOODING

Other types of flooding can also occur and the most common of these is coastal flooding. Stormy weather conditions associated with deep, cyclonic low pressure systems can give rise to a storm surge. If this coincides with the timing of a high tide, then the temporary rise in sea level can top flood defences and give rise to coastal flooding at many places around the world where there are storms to deliver onshore winds.

↓ Monsoon rains occur every year in many tropical regions. Just a 10 percent increase in average rainfall can cause major flooding, with lives lost and devastating impacts on agriculture.

DROUGHTS

Unlike many weather and climate extremes, droughts start slowly. Persistent weather patterns can lead to a slowly accumulating rainfall deficit and, as the deficit builds, soil moisture declines and river and groundwater levels fall. The lack of soil moisture means that more of the energy arriving from the Sun goes into warming the land surface than evaporating water, and this exacerbates the high temperatures often associated with drought. Marking the exact start and end to a drought is difficult, but they can last for weeks, months, or even multiple years, as happened during the 1930s Dust Bowl (see Chapter 6, page 80).

SAHEL DROUGHT

One of the worst droughts in living memory occurred in the Sahel region of West Africa in the late 1970s and early 1980s when a decade-long drought devastated crops and caused widespread famine. At the time, there was concern that the region was turning into an extension of the nearby Sahara desert and that the main cause was land mismanagement. However, we now know that the Sahel drought was at least partly driven by slow variations in ocean temperatures and enhanced warming of the southern oceans relative to those in the north. This displaced tropical rainbands southward and away from the Sahel. Later in the 1980s, these ocean patterns changed and although individual years have experienced further droughts, Sahel rainfall has generally increased since the 1980s.

ENSO AND DROUGHT

Not all droughts have an obvious cause, but the El Niño–Southern Oscillation (ENSO)—see Chapter 5, page 60—is implicated in many large-scale droughts. Droughts are more likely in southern Africa, India, and the Amazon during El Niño, whereas California and East Africa are more prone to drought during La Niña. Some of these regions experience multiple years of drought when ENSO conditions persist; the wildfires of California and the persistent drought of East Africa between 2020 and 2022 have been connected to three consecutive years of La Niña conditions.

Just about any part of the world can experience drought, and droughts are predicted to increase in frequency and intensity due to climate change and global warming. It is now thought that drought affects more people than any other form of natural disaster.

← Prolonged lack of rainfall drives drought, heavily impacting people, agriculture, economies, and ecosystems. Droughts occur on all timescales, lasting from weeks to years.

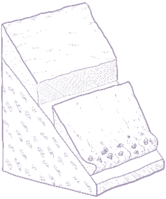
EXTREME RAINFALL AND LANDSLIDES

Landslides are the mass movement of rock and earth downslope. They often occur suddenly and unexpectedly and they move at a rate that far exceeds any chance of escape for those below. Although landslides often have multiple causes, such as earthquakes and volcanoes, the major culprit by far is heavy rainfall.

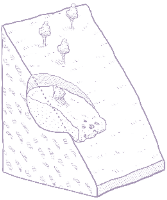
SIERRA LEONE, 2017

Many landslides occur in remote regions and can be viewed as part of the natural weathering processes of the Earth's surface. However, others are much closer to home and create human disasters. One of the worst landslides of recent decades occurred in August 2017 in Freetown, the capital city of Sierra Leone on the west coast of Africa. The city had been subjected to days of heavy rainfall, which, coupled with destabilizing deforestation, led to the collapse of a large section of Sugar Loaf mountain, overlooking Freetown. The mudslides hit in the early hours of the morning and more than 1,000 lives were lost.

↓ Rain lubricates slip surfaces between rock layers, causing landslides. If it gets into sedimentary rocks with clear bedding, it can form a planar slip surface and lead to a translational landslide.



↓ If rainfall penetrates a curved, "spoon-shaped" slip surface, it leads to a rotational landslide, which tends to self-stabilize as material piles up at the base.



→ Persistent rainfall can destabilize hillsides by penetrating deep into soils and rocks. This creates a slip surface and leads to a catastrophic failure as the landslide occurs. Landslides are commonly "spoon-shaped," rotational type, or planar translational type, depending on the underlying geology.

WHAT'S POSSIBLE?

In this chapter we've looked at some of the most extreme weather and climate events seen in recent decades. In recent years, we have seen weather records smashed time and again. Heatwaves, drought, and rainfall records devastate crops, create destruction, and take lives.

CHAOS

We know that the atmosphere is "chaotic," meaning that only the statistics of weather are bounded by the current climate, and on individual days or weeks (see Chapter 8, page 100), individual events could easily evolve far differently due to the smallest of variations in the weather beforehand. In this case, we can ask: what's possible? How extreme could weather be? What's the worst-case scenario and could it be more extreme than has yet been seen?

COMPUTER SIMULATIONS

To answer this question, scientists working on weather and climate have used computer simulations of the atmosphere, altered by tiny but plausible amounts at the start of the simulation to generate a whole spectrum of ensuing weather patterns. Note that the computer models are based on the same equations that govern the atmosphere and while the exact weather patterns they produce are different in detail, they can be statistically indistinguishable from the real-world observations, and we can use the output of thousands of simulations with these models to explore what is possible and what is the worst case for extreme weather.

WEATHER RECORDS

The global average temperature for the year reached a new high in 2016 and daily records of the global temperature measure were broken three times in one week in 2023. On regional scales, record temperatures continue to occur in multiple locations worldwide. Meteorologists in the United Kingdom had been shocked when forecasts started to predict 40°C (104°F) for the first time. Nevertheless, it was then observed in summer 2022. German forecasters were horrified to see intense summer rainfall in their forecasts as a slow-moving cyclone faltered over the country in July 2021 and delivered record rainfall and devastating floods.

UNPRECEDENTED EXTREMES

The outcomes of these computer model experiments are a sobering call to be prepared for extreme weather. Almost without fail, they show physically plausible weather events more extreme than anything seen before. These include extreme heatwaves in China and the United Kingdom, as well as record-breaking temperatures that would be off the scale compared to current measurements. There are physically plausible rainfall levels that would smash the records and deliver unprecedented flooding. Indian monsoon droughts are simulated that are three times more intense than usual and well beyond even the most severe drought of the 20th century. These simulated events have not been seen so far, but the point here is that they are simulated by the same weather models we use to predict the weather every day and to make successful forecasts and simulate climate change. The models are tried and tested, and, while not perfect, in many senses they are indistinguishable from the real weather, so we should heed their warnings. These unprecedented events, while extreme and record-breaking, are possible now and, as far as we know, any one of them could occur in the coming year.

NORTH ATLANTIC OSCILLATION

For countries around the North Atlantic basin, winter conditions can be quite different from one year to the next. Some years are marked by very mild winters, while others are intensely cold. If we look at the differences between one winter and another, we often see a similar pattern: the North Atlantic Oscillation (NAO). The NAO is the single most important factor that determines the harshness of winter in North America, Europe, and North Africa.

↓ Snow in many parts of northern Europe and eastern USA is linked to the NAO. When the NAO is in its negative phase, the Atlantic jet stream weakens and cold air floods in.

Sir Gilbert Walker, a British meteorologist, first defined and named the NAO after studying weather records in the 1920s. It has a particular pattern with low pressure over Iceland and high pressure over the Azores islands. When the NAO is positive, this pattern is strengthened and the pressure across a broad region centered over Iceland is lower than normal, while that in a broad region over the Azores is higher than normal. In this phase, the Atlantic jet stream has strengthened and moved northward and this means that northern Europe is milder than usual but also wetter and stormier as more Atlantic cyclones arrive there. In contrast, the Mediterranean and North Africa are cooler during this positive phase of the NAO. These effects also extend over the western side of the Atlantic basin, where the eastern United States is mild and eastern Canada is colder when the NAO is positive. Overall, this gives a four-fold pattern of temperature and it means that east coast United States temperatures vary with those in northern Europe.

CLIMATE VARIABILITY

The NAO has varied dramatically and caused some extreme winters in the past. During the winters of the 1960s, the NAO was often in its negative phase and northern Europe experienced some of its coldest winters of the 20th century. Then during the 1990s, the NAO flipped into its positive phase and a string of mild winters in northern Europe were marked by flooding and storm damage. These fluctuations continue and 2009/10 experienced the lowest NAO on record with intense cold and heavy snowfall across much of Europe, while the winter of 2019/20 had a positive NAO, with a battery of Atlantic storms and record late winter rainfall in the United Kingdom. Understanding and predicting these fluctuations is a hot topic with meteorologists.

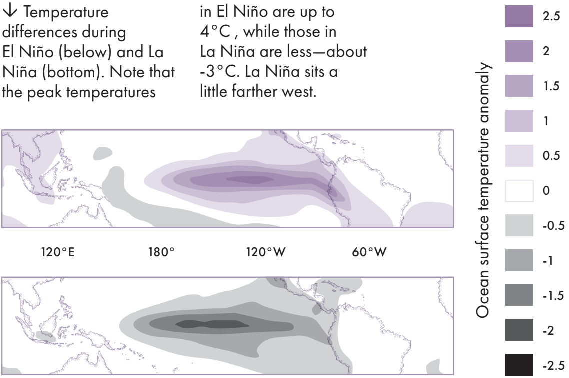
EL NIÑO AND LA NIÑA

The largest, naturally occurring weather change from one year to the next is the El Niño–Southern Oscillation (ENSO). It comes in two phases, corresponding to warming (El Niño) or cooling (La Niña) of the tropical Pacific. Differences between La Niña and El Niño are just a few degrees of ocean temperature, but the impacts on world weather are far-reaching. Even global temperatures are affected and every degree of El Niño warming gives a temporary increase of about 0.1 degree in global temperature the following year.

ORIGINS

The El Niño and La Niña names are Spanish for "the boy" and "the girl," respectively, and they originate from the local inhabitants of South America who were all too familiar with the episodic changes in their climate. The name refers to the Christ child, as ENSO cycles tend to peak around Christmas. Rainfall and temperatures along the west coast of South America closely follow the ENSO cycle and fish catches rise during La Niña and fall during El Niño as the amount of nutrient-rich water is modulated.

↓ Temperature differences during El Niño (below) and La Niña (bottom). Note that the peak temperatures in El Niño are up to 4°C, while those in La Niña are less—about -3°C. La Niña sits a little farther west.



ENSO is coupled to the atmosphere and the ocean. As ocean temperatures cool along the equatorial Pacific during La Niña, the Pacific trade winds strengthen so that La Niña years are the best for trade ships to cross from South America to Asia. We know that ENSO cycles have been going on for many years, since Peruvian fishers have been following them closely to guide their fishing. This has now been extended to many thousands of years using coral records, which show periodic bleaching from the hot ocean conditions that come and go with ENSO.

CLIMATIC EFFECTS

The cycle usually ramps up in the summer and one of the first regions affected is India, where the monsoon rains often falter during El Niño, giving rise to droughts and reducing crop yields. ENSO cycles reach their peak at the end of the year and the eastward shift or rainfall during El Niño leaves behind drought and wildfires across West Pacific countries and northeastern Australia. The rainfall and rising air over the East Pacific is balanced by descent over northern parts of South America, and the Amazon rainforest also suffers from droughts and increased wildfires. Knock-on effects are felt as far away as southern Africa, which suffers from serious droughts during El Niño, and even northern Europe is affected, with colder, drier winters during El Niño and wetter, stormy winters during La Niña. Even after ENSO subsides in April, it leaves behind further weather changes in store; the summer monsoon in China is often supercharged following big El Niños, giving rise to flooding and destruction in the Yangtze River valley.

PREDICTABILITY

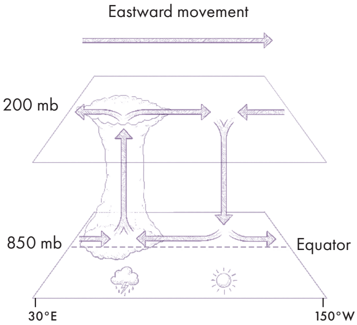
El Niño and La Niña are also among the most predictable phenomena in Earth's climate. Computer models, loaded with observations of what the ocean and atmosphere are doing today, can predict the cycle out to many months ahead and, in some cases, when a big El Niño is looming, forecasts can predict it more than a year ahead. This is crucial for some parts of the world, as ENSO cycles can drive droughts and floods across the whole globe.

MADDEN–JULIAN OSCILLATION

The Madden–Julian Oscillation (MJO) is the largest source of month-to-month changes in tropical weather. It was discovered recently, in the 1970s, as weather data gained greater coverage and revealed its prominent cycling, roughly every 40 days. There is a convective center to the MJO, with upward motion and heavy rainfall, balanced by neighboring descent and clear skies. However, the MJO is a traveling phenomenon and the whole pattern marches from west to east across the tropics at a speed of around 20 km/h (12 mph).

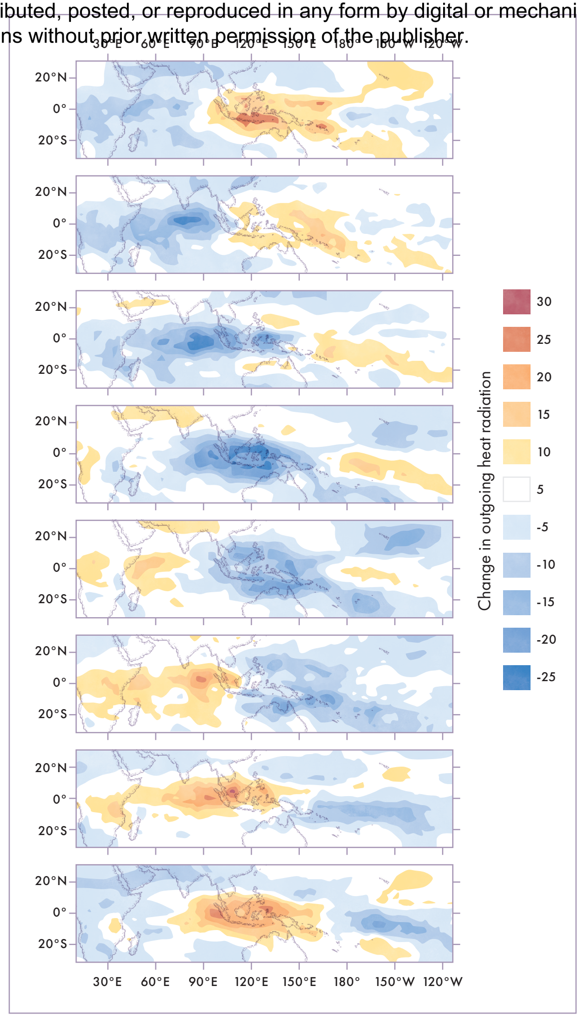
CONVECTIVE CORE

The convective center of the MJO is ripe for thunderstorms and even tropical cyclone development, so the risk of Pacific typhoons and Atlantic hurricanes varies with the MJO cycle. It also reaches into the extratropics, where it changes North Pacific winds, and as its center of high rainfall moves to the central Pacific, there is often heavy rainfall over western North America. The MJO even affects European weather, where it can help drive intense winter cold snaps.



↙ The MJO contains a region of strong convection with rising air that flows outward in the upper troposphere as it moves slowly eastward. It affects typhoons and weather out into the extratropics.

→ The MJO dominates tropical weather variations from month to month, from the Indian Ocean to the Pacific. It moves eastward over 40–60 days. Intense periods of MJO activity can trigger El Niño events in the East Pacific.


30°E
60°E
90°E
120°E
150°E
180°
150°W
120°W
20°N
0°
20°S
Change in outgoing heat radiation
30
25
20
15
10
5
-5
-10
-15
-20
-25

SUDDEN STRATOSPHERIC WARMING

The winter stratosphere is home to the largest cyclone on the planet—the stratospheric polar vortex. With low pressure over the pole, temperatures many tens of degrees below zero, and strong westerly winds circling the planet, this planetary-scale winter vortex is ripe for one of the most dramatic weather events on Earth.

DISCOVERY

This was first noticed by Richard Scherhag, a German meteorologist who had started to compile regular balloon-borne observations of the stratosphere. In early 1952 he published the results of his observations, which showed a startling change. The temperatures over the Arctic in the winter stratosphere showed a sudden and unexpected increase of many tens of degrees in just a few days. Nowhere else in the atmosphere had such a dramatic warming ever been observed and it prompted Scherhag to call it “explosive.” Scherhag had witnessed the first recorded sudden stratospheric warming.

WEATHER IMPACT

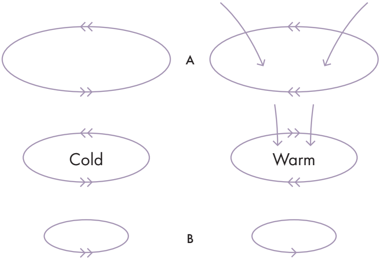
After regular observations and monitoring became available and there were enough events to make a good-size sample, it was noticed that the period following a sudden stratospheric warming was often cold over northern Europe and the eastern United States. It turns out that the warming in the lower stratosphere, accompanied by weak or easterly winds as the vortex collapses, has an influence on the weather below and even at the surface. In the last few years, after intense cold and snow events following sudden stratospheric warmings like the one in early 2018, this high-altitude phenomenon is now one of the regular tools that long-range forecasters use to predict the weather.

MECHANISM

The air in the stratosphere is tenuous and, compared to the much higher density troposphere, changes in stratospheric winds can be rapid and dramatic. It was not until 20 years later, in the 1970s, and through the observation of a number of other sudden warming events, that Japanese meteorologist Taroh Matsuno presented a solution to what caused the rapid warming. In fact, there is no heating going on at all during a sudden stratospheric warming. Instead, the winds around the polar vortex are decelerated by enormous atmospheric waves that break on the edge of the vortex, causing the air to fall into the polar vortex, where it is compressed and therefore warms in a manner similar to the warming of the air in a bicycle pump as it is compressed to inflate a tire.

FREQUENCY

Sudden stratospheric warmings occur relatively frequently in the Northern Hemisphere and on average we see them in five or six winters per decade. However, this varies a lot and in the 1990s there was a run of almost ten years with no sudden stratospheric warmings at all. Southern Hemisphere events are much rarer and the first event was not recorded until 2002, when it took meteorologists by surprise. Since then, computer model experiments have been used to simulate thousands of virtual winters and estimate that we should see sudden warming events in the Southern Hemisphere roughly every 25 years on average.



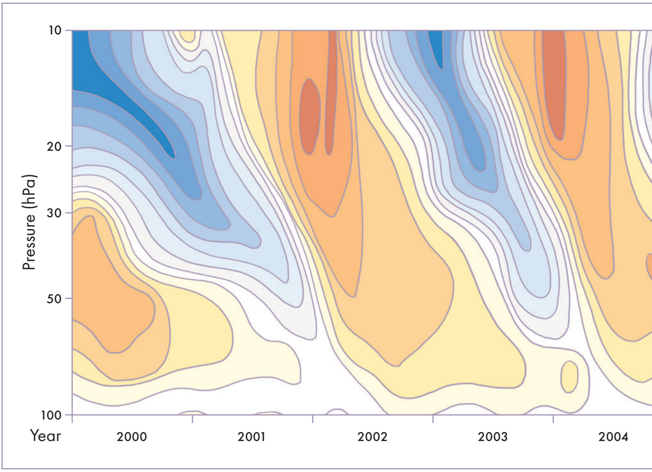
→ The usual westerly winds in the polar vortex (left) collapse during a sudden stratospheric warming and air floods into the Arctic (right), compressing and warming as it sinks through the stratosphere (A) and leading to high pressure in the troposphere (B).

QUASI–BIENNIAL OSCILLATION

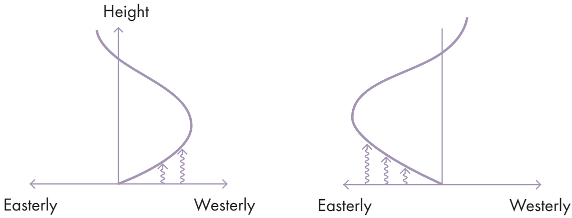
The regularity of the Quasi–Biennial Oscillation (QBO) is utterly remarkable. It consists of alternating westerly and easterly wind cycles that migrate slowly downward through the stratosphere, terminating at the boundary with the troposphere. These winds go right around the Earth in a belt in the QBO and so if you chart them by height and time over a number of years, you get a striking series of stripes as the oscillation flips from one state to the other.

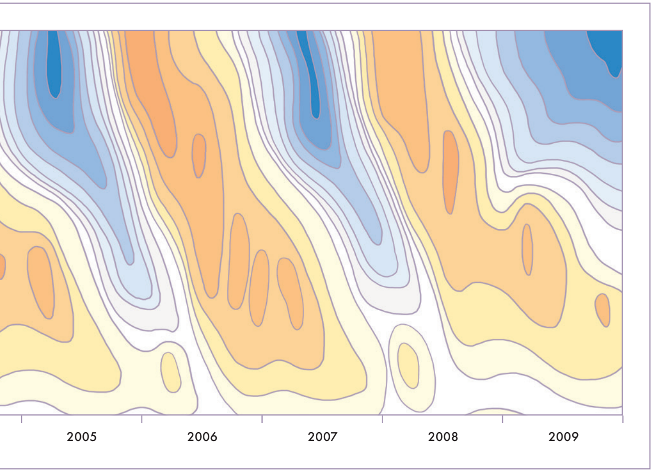
↓ After the seasonal cycle, the QBO is the most regular feature of our atmosphere. It consists of oscillations between westerly (yellow) and easterly (blue) winds circling around the Equator at high altitude and propagating down through the atmosphere. The striking cycles of the QBO can now be reproduced in our computer models of the weather.

→ The QBO is driven by atmospheric waves that propagate up from the troposphere and approach the QBO from below, where they break like waves on a beach and drive the oscillation.



The winds are a little stronger and migrate downward a little more slowly in the easterly phase, but the QBO is the most predictable variation in the atmosphere and skillful forecasts are possible even years ahead. The QBO is all the more remarkable because its regular cycles are not forced by the Sun or other external driver. Instead, it arises spontaneously within the atmosphere in a process akin to longshore drift in the ocean.





PACIFIC AND ATLANTIC VARIABILITY

Weather and climate fluctuations from day to day are usually greater than those from month to month, which in turn usually exceed those from year to year and so on. However, the decade-to-decade variations of the surface Atlantic Ocean are an exception. So-called Atlantic Multidecadal Variability (AMV) shows larger variations on decadal timescales than are seen from year to year. This unusual phenomenon fluctuates with changes in the poleward flow in the Atlantic Ocean that push more/less warm water poleward and create warm/cool Atlantic ocean conditions in the positive/negative phase. AMV stimulates droughts in North America and Africa and creates slow, decade-long variations in European summer weather and the strength of the Atlantic hurricane season.

PACIFIC CLIMATE

Although it is different in character, there is also prominent decadal variability in the Pacific Ocean. So called Pacific Decadal Variability (PDV) is closely related to multiyear variations in the cycling between El Niño and La Niña, although some climate scientists argue that it is independent. In the positive phase, the PDV displays warm conditions in a broad swath across the tropical Pacific. PDV also has far-reaching consequences, with regional climate effects similar to El Niño and La Niña and recent evidence that it was a key player in the so-called "global warming slowdown" of the early 21st century when it helped to temporarily slow the rate of global warming. PDV also changes the frequency of cold snaps over China from one decade to the next and it has a well-known impact on salmon abundance and fish catches off the coast of Alaska, which are enhanced when the PDV is in its warm phase.

ATLANTIC-PACIFIC LINK

Although they are separated by the Americas, Atlantic and Pacific decadal variations are now known to be connected. Analysis of historical climate records and experiments with computer models of the climate show that when the Atlantic warms it tends to trigger Pacific cooling. Although the changes are just a fraction of a degree, if the two ocean basins change in concert, they can trigger extreme events like the 1930s Dust Bowl (see Chapter 6, page 80).

← Decade-to-decade variations in summer rainfall in Europe are linked to Atlantic Multidecadal Variability.

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