

## Weather, extreme

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Weather affects all facets of life on Earth. Atmospheric elements such as precipitation, temperature, and wind are ordinarily considered resources supporting habitats and rudiments necessary for animal and plant survival and well-being. However, when a particular weather element deviates from a normal band of tolerance for life, it transitions from a resource into a hazard. These extremes combine with human and environmental sensitivities to create negative consequences and, in some cases, disasters.

Weather extremes are typically referred to as “storms,” which are atmospheric disturbances driven, in large part, by the foundations of our Earth-atmospheric system including: differential heating of the surface of the Earth by the sun, the heating of the lower atmosphere by energy transfer from the Earth’s surface, and Earth’s rotation and varied topography. Storms are important in redistributing excesses in energy found in the Earth-atmospheric system; however, in trying to seek an insatiable energy balance, these storms generate weather elements such as pressure extremes, high winds, intense precipitation rates, and other hazards that can be detrimental to society.

Large-scale storms typically arise as regions of low pressure that are characterized by winds rotating cyclonically (hence, their meteorological

name, “cyclones”). These cyclones derive their classification – extratropical or tropical – depending on their meteorological and geographic origins. Smaller, or mesoscale, disturbances can create localized hazards that are often driven by deep, moist convection in the troposphere, or thunderstorms. However, in the absence of these atmospheric disturbances, sustained quiescent weather conditions can, somewhat paradoxically, lead to climatological extremes such as drought or heat waves.

### Extratropical cyclones

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Extratropical cyclones are the primary generator of weather extremes in the mid-latitudes (30–70°). Studies as far back as the late nineteenth century recognized the important effects these cyclones have on the day-to-day variability and hazard-scapes in extratropical regions. Extratropical cyclones are large swirling areas of low pressure that are characterized by air mass fronts and are generated dynamically by the Earth’s rotation in combination with the instability caused by the uneven heating of the Earth’s surface. Storm initiation, or cyclogenesis, is provoked by upper-level disturbances, or troughs, embedded in regions of enhanced winds within the jetstream, or jetstreaks, that create diverging air currents near the tropopause. Cyclogenesis is climatologically focused where extreme gradients in orography (leeward of a mountain range) or low-level atmosphere temperatures (warm ocean current with nearby cold landmass) exist. Intense extratropical cyclones occur most frequently in the Southern Hemisphere near New Zealand, east of South America, and in the southern

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Indian Ocean and in the Northern Hemisphere near east-central North America, the northern Atlantic, Europe, Far East and northwest Pacific, and south-central Asia.

In the high latitudes, cyclones with similar spiraling structures to their mid-latitude counterparts, but smaller in spatial ( $\approx 100$  km in diameter) scale, are known as polar lows or, colloquially, arctic hurricanes. These events are particularly dangerous to mariners due to their forecast difficulty and rapid onset of extreme winds and snow. In the Northern Hemisphere, these severe events most commonly form and affect the areas near the Davis Strait and Labrador Sea, Baltic Sea, and Gulf of Alaska and Bering Sea.

Extratropical cyclones have the propensity to rapidly develop and intensify after their inception, lasting from a few days to over a couple weeks; the lengthier lifetimes occur when a cyclone becomes “cut-off” from the jet stream and gradually dissipates. Climatologically, cyclones tend to dominate the cool and transition seasons in each hemisphere, promoting a wide spectrum of hazards, from blizzards and ice storms on the cool side of the cyclone to tornado outbreaks, lightning, hail, severe non-tornadic winds, and flooding in the cyclone’s warm sector. Cyclones cover extensive geographies, with each storm encompassing from one to three thousand kilometers at maturity and traversing wide expanses of their hemisphere. Not all extratropical cyclones produce the spectrum of weather extremes, but due to their great size, regularity, and strong dynamics, they are more responsible for weather hazards than any other storm phenomenon. In particular, events that undergo explosive cyclogenesis, or exceptionally rapid deepening of a storm’s center of low pressure, are disproportionately more likely to produce hazards due to their intense dynamics. These events are classified by meteorologists as “bombs” and, in the Northern Hemisphere, are

most frequent during the cool and transition seasons along the Canada and US east coast, northern Atlantic and northwest Europe, as well as the north-central and far northwestern Pacific.

Extratropical cyclones and their affiliated fronts can promote extensive changes in sensible weather over short periods of time. Severe winter weather most frequently manifests on the poleward side of cold and warm fronts in extratropical cyclones. If an extratropical cyclone draws in a polar air mass that is sufficiently deep and cold, it can be branded a “winter storm” containing life-threatening cold temperatures, high winds, heavy snow, ice pellets, and/or freezing rain. Winter weather hazards are capable of negatively impacting public safety and human systems, with high-end events damaging infrastructure and utilities, halting transportation systems, restricting socioeconomic activities, and harming or killing livestock and cultivated plants. In particular, blizzards and ice storms can paralyze regions, impacting millions of people and causing billions of dollars in agricultural, property, utility, and productivity losses, as well as casualties (e.g., frostbite, hypothermia, or injuries sustained in weather-related vehicle crashes). Extreme cold air outbreaks into the middle and lower latitudes occasionally follow strong extratropical cyclone passages in the cool season. These cold waves can result in billions of dollars in economic loss (primarily in the agricultural sector) and can cause thousands of fatalities in exceptionally vulnerable regions.

The term blizzard is loosely applied to any heavy snowstorm; though, few snowstorms exceed official blizzard criteria employed by government forecast agencies. For example, the US National Weather Service (NWS) defines a blizzard as an event that has snow and/or blowing snow reducing visibility less than four tenths of a kilometer and sustained winds of  $15.6 \text{ m s}^{-1}$  for at least 3 hours. A global blizzard

climatology does not exist, but these events are most commonly experienced poleward of the climatological track of intense, cool season extratropical cyclones, with formation occurring on the leeside of mountain ranges and within or adjacent to arctic air mass source regions. For example, in North America, blizzards most commonly affect the interior portion of the continent including large expanses of the north-central United States and central Canada prairies. On average, one to two blizzards per year can be expected in these regions.

Though less frequent than their interior continental counterparts, blizzards can be generated by powerful low-pressure systems fostered by dramatic low-level temperature gradients that predominate where warm coastal waters border cool landmasses. In North America, these coastal lows develop near the northern Gulf Coast or Cape Hatteras and intensify as they move to the northeast United States and Atlantic Canada. These coastal extratropical cyclones, called nor'easters, are particularly noteworthy due to their litany of hazardous effects – from blizzard conditions, hurricane-force winds, precipitation type variability and extreme rates, to coastal flooding and erosion. On average, approximately 12 of these coastal cyclones occur per cool season, with two or three producing significant impacts on the amplified population and infrastructure found along the east coast. Similar extratropical cyclones occur regularly during the cool season across northern Japan and northwestern Europe.

Drizzle and rain falling into air near the surface at or below the freezing point can promote ice accumulations that may have significant influences on energy and transportation systems. While minor ice accumulations, or glazes, can lead to vehicle crashes and pedestrian accidents, significant accumulations ( $\geq 6.35$  mm) produced by ice storms can cause incredible damage to

power distribution systems, as well as commercial and personal property due to felled trees. In North America, climatologies reveal that freezing rain and drizzle occur in about a quarter of all winter events, and are most frequent during the cool season (December–March) across central and eastern portions of the United States and Canada, Alaska, and the northern shores of Canada. Freezing precipitation events and ice storms have a propensity to develop poleward of fronts or within cold air damming or trapping patterns. In the instances of damming or trapping patterns, the cold air becomes entrenched in the low levels of the atmosphere due to airflow blockage caused by terrain barriers such as mountains. This unique effect occurs on the east side of orographic barriers in central (Rockies) and eastern (Appalachian) North America, Europe (Alps), South America (Andes), and the Far East.

### Severe local storms

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Smaller scale, but equally impressive, weather phenomena occur as a result of the formation of deep, moist convection. When atmospheric conditions are favorable, specifically in regards to the vertical variation in temperature and wind, thunderstorms can form that are capable of producing frequent lightning, large hailstones, copious rainfall, damaging winds, and even tornadoes. In the United States, the NWS defines these severe thunderstorm events as hail with a diameter of  $\geq 2.5$  cm, wind gusts of  $\geq 26$  m s<sup>-1</sup>, and/or a tornado. Commonly, these events are found within the warm sector of extratropical cyclones. However, during the warm season, severe thunderstorms are often independent of extratropical cyclones, developing wherever the basic ingredients required for their formation juxtapose.

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Three ingredients are necessary for the formation of a thunderstorm, including a moist layer of sufficient depth in the low or mid-troposphere, an unstable atmosphere, and a lifting mechanism. Essentially, thunderstorms form as theoretical volumes of air accelerate upwards due to differences in density when compared to surrounding air. This process is efficient at relieving the accumulation of potential energy caused by differential heating of Earth's surface. While thunderstorms are most common in tropical regions, these storms are often short-lived and rarely meet severe weather criteria. In order to obtain more organized thunderstorms capable of producing severe hazards, an additional ingredient must be added – wind shear. This shear, which is a change in wind speed and/or direction with atmospheric height, promotes a separation in the thunderstorm's updraft and downdraft region, as well as the development of distinctive internal dynamical processes. The addition of wind shear increases the strength and longevity of thunderstorms, often engendering so-called supercell thunderstorms, which are the strongest thunderstorms on Earth. These relatively rare thunderstorms are characterized by their powerful rotating updrafts, or mesocyclones, and ability to produce Earth's most violent weather. In fact, most strong tornadoes and severe hailstones originate from supercell thunderstorms.

Large clusters of thunderstorms that undergo a mode of self-organization are known as mesoscale convective systems. Found in many tropical and subtropical areas around the world, these complexes are very beneficial to regions dominated by rain-fed agriculture. However, these thunderstorms systems can cause floods, extreme lightning rates, and extensive severe nontornadic wind events known as derechos.

The central United States is home to the world's highest frequency of severe thunderstorms. The relatively flat topography of the

Great Plains allows for little obstruction between warm, humid air positioned over the Gulf of Mexico and its interaction with hot, dry air from the high terrain of the Chihuahuan Desert and cool, dry air originating from the Canadian Prairies. If sufficient wind shear overlaps these intersecting air masses, severe thunderstorms can result. Statistically, this is most likely to happen in the United States during the period April through June when over half of all annual severe weather reports occur. Tornadoes, which are arguably the least understood of all hazards, are also most common in this region and exhibit a relatively predictable annual cycle of occurrence. Throughout the cool season, tornadoes, while climatologically rare during this time of the year, are most frequent in the extreme southern portions of the United States due to that region's proximity to warm, moist air from the Gulf of Mexico. During early spring, tornadoes surge in frequency and tend to be most common in the southern Great Plains before migrating to the northern Great Plains and Canadian Prairies during summer. This occurs as solar declination shifts toward the Tropic of Cancer, forcing wind shear and lifting mechanisms affiliated with the polar jet stream and its disturbances toward higher latitudes.

Globally, other locations (e.g., Argentina, Australia) also exhibit similar seasonal cycles of tornado occurrence. However, since severe weather reports are biased to areas of population, climatologists favor analyzing data related to the aforementioned ingredients necessary for their formation. Global climatologies of severe weather ingredients reveal local maxima concentrated in equatorial and southern Africa, southern Europe, the central United States, southern Brazil, northern Argentina, eastern Australia, and adjacent to the Himalayas. Such environments are most common in transition seasons, when

low-level temperature gradients are maximized and extratropical cyclones are abundant.

Severe weather can have large socioeconomic consequences, especially during so-called outbreak events of significant magnitude, frequency, and spatial coverage. For example, severe thunderstorms in the southeast United States during April–May 2011 spawned tornadoes responsible for US\$17.3 billion in damages and at least 350 fatalities across 20 states. Extremely devastating tornadoes such as these may rank as EF4 or EF5 on the enhanced Fujita tornado intensity scale. While only 2% of all recorded US tornadoes are rated EF4 or EF5, they are responsible for nearly 68% of all tornado fatalities. In extremely vulnerable countries, the death toll from tornadoes can be enormous; for instance, in April 1989 nearly 1300 people were killed in Bangladesh in a single event. The recent increasing trend of economic losses from severe thunderstorms and tornadoes can be attributed to societal changes rather than any detectable increase in event frequency. However, recent research has indicated that the potential exists for an increase in severe thunderstorm environments under future anthropogenically driven climate change scenarios.

### Hydrologic extremes

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Floods are one of the costliest and deadliest hazards due to their relatively high rate of occurrence and the extensive human habitation of river floodplains and coastlines. Nearly 10% of the global population lives in flood-prone areas. According to the International Disaster Database, non-geophysical floods were responsible for nearly 4000 disasters from 1979 to 2013, affecting approximately 3.3 billion people and killing 230 000. An estimated US\$600 billion in damages were blamed on floods during this

period. Historically, floods have been immense killers, particularly in parts of Asia. The deadliest natural disaster (excluding pandemics and famines) in the history of the world occurred in central China along the Yangtze and Huai Rivers in 1931, when between 1 million and 4 million people were killed.

Floods are classified based on their geography, sources, and rapidity. The deadliest events are associated with quick-onset coastal storm surges accompanying tropical and strong extratropical cyclones (geophysical events such as earthquakes and sub-marine landslides can cause surges, or tsunamis, as well) and flash floods, which are localized, short-duration events often produced by flood control structure failure and/or high rainfall rates in thunderstorms. Due to their swiftness and localized nature, surge and flash flood location and magnitudes are difficult to forecast. Widespread floods are more predictable and can transpire over days, weeks, or even months when excessive rain and/or snow melt occurs in river basins. The intensity, extent, and frequency of precipitation events are important flood determinants, but other contributing factors such as watershed orientation in relation to the precipitation footprint, orography and slope, infiltration rates and saturation of soils, vegetation, land use (e.g., urbanization, deforestation, fallow fields), snow melt and ice jams, and flood control structures (e.g., levees, dams) can influence the occurrence and degree of flood.

Tropical cyclones produce exceptional rates of rainfall, leading to flash and widespread floods not only at landfall locations, but inland areas affected by decaying and remnant systems. Climatologically, rainfall contribution from tropical cyclones is most pronounced over southeast North America, Central America, the Caribbean, countries abutting the Bay of Bengal, far southeast and eastern Asia, northern Australia, and Madagascar. Floods can also be

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triggered by monsoons, which are seasonal reversals in regional wind circulations and precipitation produced by stark contrasts in surface heating over continents and nearby oceans. The monsoon is most prominent in south Asia, but weaker (and sometimes, incomplete) seasonal reversals in wind and precipitation occur in west and sub-Saharan Africa, the Mojave and Sonoran deserts of North America, northern Australia, and parts of Indo-China into Japan. In the last case, a front between poleward cool, dry air and equatorward warm, moist air can become quasi-stationary during the warm season. This front, known as the Mei-Yu, can trigger the continual development and training of large thunderstorm complexes, exacerbating rainfall totals. The front has a tendency to align itself along the Yangtze River basin, which can result in enormous and deadly floods. In this region, seven flood events were responsible for over 100 000 deaths each during the twentieth century.

Though tropical cyclones and monsoons are important genitors of floods, most damaging and casualty-producing flood events are caused by localized heavy rains produced by thunderstorms. Climatologies of floods caused by these intense rain events are difficult to assess due to data inconsistencies, lack of reporting, and overrepresentation of cases in some countries. However, reported floods caused by torrential rainfalls are most frequent in East and Southeast Asia, the Indian subcontinent, eastern Africa, Central America, eastern United States, and Europe.

Conversely, extended periods of precipitation deficiency can lead to drought. Drought is a particularly difficult concept to recognize and comprehend due to its slow onset, multifaceted effects on and interactions with human-environmental systems, complexity in identification due to the lack of a universal causative source, and its relativeness to each locale's hydroclimatology. In vulnerable regions,

drought can prompt disasters with immense death due to famine and prolonged military conflict that, ultimately, has resulted in some of the world's greatest human tragedies. Like floods, droughts can occur in almost every region of the globe, but the most devastating human calamities instigated by drought in the past century have occurred in the sub-Saharan Sahel and China. Similar to droughts, heat waves are weather extremes that occur absent storms. These events are particularly deceptive due to their high human mortality without visceral images of damage.

### Tropical cyclones

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Tropical cyclones, which include hurricanes (Atlantic and eastern Pacific Ocean basins), typhoons (western Pacific), and severe cyclones (Indian), are the most destructive storms on Earth. When these spiraling storms interact with developed landscapes, significant losses to economies and life can occur. For instance, the deadliest weather disaster in the past half century was Cyclone Bhola, which devastated the northern Bay of Bengal coastline in 1970. The costliest weather disaster in history was Hurricane Katrina, which ravaged the central Gulf Coast of the United States in 2005.

Tropical cyclones develop from clusters of thunderstorms that persist over tropical ocean waters in an environment with little or no vertical wind shear. The Coriolis force (due to the rotating Earth) causes the incipient thunderstorm complex to rotate; this force becomes negligible at latitudes less than 5° and, for this reason, tropical cyclones do not form near the equator. Tropical cyclones obtain energy for formation and sustenance from warm seas through sensible and, most importantly, latent heat transfer. Warm oceans readily evaporate water and, through this process,

heat is extracted from the sea surface. This heat is reserved, or held latent, until it is re-released into developing tropical thunderstorms when water vapor condenses in storm updrafts. The tremendous rates of condensation that occur in a tropical cyclone promote a warm-core system, indicating that temperatures in the center of the cyclone are warmer than the areas at the same altitude surrounding the core; this is counter to extratropical cyclones, which feature cold cores.

A tropical cyclone structure includes a tight center of descending air that forms a small area absent of convection known as the eye. Surrounding the calm eye is a ring of deep convective torrents called the eyewall. It is within this relatively narrow region where the storm's most significant hazards, including wind and surge, transpire. Outside of the eyewall, spiraling rainbands encircle and converge toward the center of the storm. These bands include squalls of wind and intense precipitation and, in some land-falling cases, tornadoes. Mature tropical cyclones are characterized by deep low pressures at their core, promoting concentrated pressure gradients and, in turn, low-level winds that can cause extreme damage and encourage the formation of deadly storm surges.

On average, there are approximately 86 named tropical storms (greater than  $17 \text{ m s}^{-1}$  sustained winds) per year globally. Of those 86, 47 reach the minimal threshold (greater than  $33 \text{ m s}^{-1}$  sustained wind) to be considered a hurricane, typhoon, or tropical cyclone. Two thirds of all tropical cyclone activity occurs in the Northern Hemisphere, with the northwest Pacific basin the most active (mean of 26 named storms per year), followed by the northeast Pacific (17), Atlantic (12), southwest Pacific (10), and southwest Indian (9) ocean basins. Interannual variability in the number of events per basin is significant and is dependent on the seasonal character of sea surface temperatures, the strength of the wind

flow in the troposphere, and ambient humidity in development regions.

The northwest Pacific is the only basin that experiences year-round tropical cyclones. Tropical cyclone activity in other basins is most common after a seasonal maximum in the solar declination. For instance, in the Atlantic and eastern Pacific basins, hurricane activity extends from late May or early June to the end of November, with peak activity typically in August and September. The north Indian (south Indian and southwest Pacific) basin typically experiences cyclones from April to December (October to May). Most tropical cyclones are characterized by westward motion during their formative and mature stages due to their usual position equatorward of semipermanent, oceanic subtropical ridges and embedment in the easterly trade winds. Thereafter, some events may curve poleward around the western flank of subtropical ridges, interact with the mid-latitude westerlies, and even transition into powerful, cold-core extratropical cyclones.

Tropical cyclone strength is most often classified based on the Saffir-Simpson scale, which ranks tropical cyclones from category 1 (at least  $33 \text{ m s}^{-1}$ ) to 5 (exceeding  $70 \text{ m s}^{-1}$ ) based on sustained wind speed. While all tropical cyclones have the potential to cause disasters, more intense landfalling events are commonly characterized by devastating winds, storm surges, and flooding rains. Indeed, a disproportionate amount of damage and loss of life is caused by “major” hurricanes (category 3 or greater on the Saffir-Simpson scale) and “super” typhoons (equivalent of category 4 or 5). Increases in coastal population, built environment, and vulnerabilities have led to amplifying impacts, especially as measured in people affected and economic loss.

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**SEE ALSO:** Climate and societal impacts; Climatology; Environmental hazards; Hydroclimatology and hydrometeorology; Natural hazards and disasters; Social vulnerability and environmental hazards

### Further reading

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