

GS GEOGRAPHY SERIES · BOOK 1 OF 4

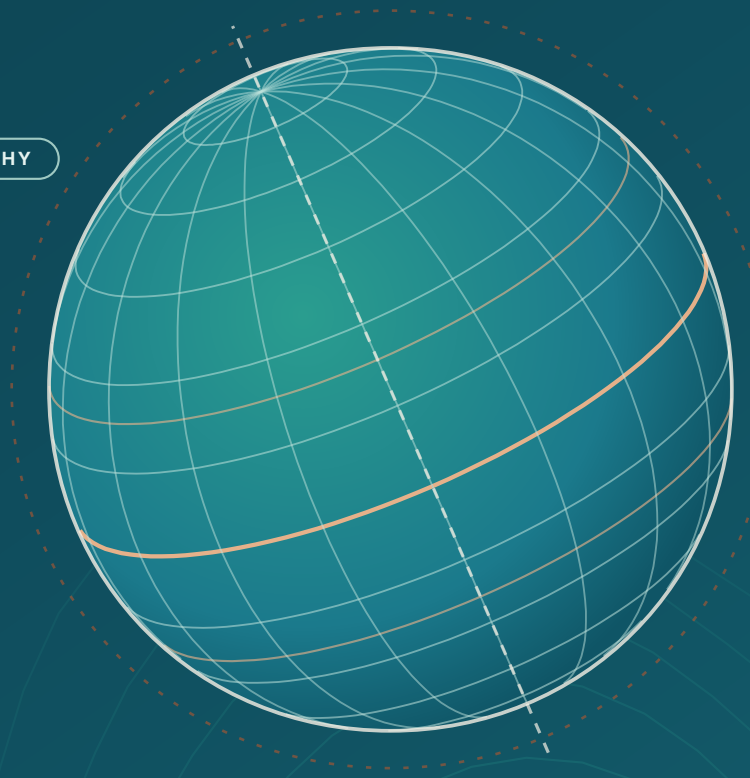
Physical Geography

Complete notes for the UPSC Civil Services Examination: Prelims and General Studies Paper I (Mains)

GEOMORPHOLOGY

CLIMATOLOGY

OCEANOGRAPHY

**28**

chapters

700+

diagrams and photos

360+

previous-year questions

2026

edition, updated to Oct 2026

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Four parts, twenty-eight chapters. Each chapter ends with its own Previous Year Questions.

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This free sample contains Chapters 1 and 20 in full. Page numbers are those of the complete book.

PHYSICAL GEOGRAPHY

PRELIMS · GS PAPER I

The Universe: Big Bang, Galaxies and Stars

Physical geography studies the Earth, but the Earth makes sense only once we know where it sits. Our planet circles an ordinary star, in one arm of an ordinary galaxy, in a universe that began about 13.8 billion years ago and is still expanding. Nearly every atom in the rocks, oceans and air, apart from hydrogen, was made inside a star that lived and died before the Sun was born.

SYLLABUS

PRELIMS

Indian and World Geography: Physical Geography of the World; General Science; current events in space

MAINS · GS PAPER I

Salient features of world's physical geography; GS Paper III: Awareness in the field of space

CONTENTS

01 The Universe and How We Measure It

03 Evidence for the Big Bang

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07 Black Holes and Gravitational Waves

09 Observing the Universe: India's Role

02 How Did the Universe Begin?

04 Expansion, Dark Matter and Dark Energy

06 Stars: Birth, Life and Death

08 Constellations and the Pole Star

10 Previous Year Questions

This chapter covers:

- the units used to measure cosmic distances, and Earth's "address" in the universe;
- how the universe began, the evidence for the Big Bang, and why it is expanding faster and faster;
- dark matter and dark energy, which together make up about 95% of the universe;
- the kinds of galaxies, the structure of the Milky Way, and the birth, life and death of stars;
- black holes, neutron stars and gravitational waves, including LIGO-India;
- constellations, the Pole Star, and the telescopes, Indian and global, that study the sky.

The next chapter takes up the Solar System and the Sun.

01 The Universe and How We Measure It

The **universe** is everything that exists: all of space and time, and all the matter and energy within them. **Cosmology** is the study of the universe as a whole, its origin, structure and fate. **Astronomy** studies the objects in it, such as stars, planets and galaxies, and **astrophysics** applies physics to explain how they work.

The universe is about **13.8 billion years old**. The part we can see, the **observable universe**, is about **93 billion light-years** across. It is larger than 13.8 billion light-years because space has kept stretching while the light was on its way.

Estimates of how many galaxies it holds run from a few hundred billion to about two trillion. Because light takes time to travel, **looking far away is also looking back in time**: we see the Sun as it was about eight minutes ago, and the Andromeda galaxy as it was 2.5 million years ago.

Units of Cosmic Distance

Kilometres are far too small for space, so astronomers use units based on the Earth's orbit and on the speed of light, which in a vacuum is about **3 lakh km per second** (299,792 km/s).

UNIT	WHAT IT MEASURES	VALUE	TYPICAL USE
Astronomical Unit (AU)	Mean distance between the Earth and the Sun	≈ 149.6 million km (sunlight takes about 8 min 20 s)	Distances within the Solar System
Light-year (ly)	Distance light travels in one year	≈ 9.46 trillion km (about 63,000 AU)	Distances to stars and galaxies
Parsec (pc)	Distance at which a star shows a parallax of one arc-second	≈ 3.26 light-years	Professional astronomy; a megaparsec (Mpc) is 3.26 million ly

A light-year is a unit of **distance, not time**. It works as a yardstick because **the speed of light in a vacuum is always the same**, whoever measures it and however fast they move. This is a principle of Einstein's relativity, and it is exactly what UPSC tested in 2021. The nearest star after the Sun, **Proxima Centauri**, is 4.24 light-years away.

Earth's Cosmic Address: From Our Planet to the Observable Universe



Fig. 1.1 Each box is far larger than the one before. Sizes are approximate; the drawings are not to scale.

02 How Did the Universe Begin?

Until the early twentieth century most scientists, Einstein included, assumed the universe was **static and eternal**. Einstein even added a "cosmological constant" to his equations in 1917 to stop the universe from expanding or collapsing. Two broad explanations then competed.

The Steady State Theory

Proposed in 1948 by **Hermann Bondi, Thomas Gold and Fred Hoyle**, the **Steady State theory** accepted that galaxies are moving apart. It argued, however, that new matter is continuously created in the gaps, so the universe looks the same at all times and has **no beginning and no end**. The theory lost support in the 1960s, when the afterglow of a hot early universe was discovered and distant (and therefore ancient) regions of space were found to look clearly different from nearby ones.

The Big Bang Theory

The **Big Bang theory** is the accepted scientific model. It says that about **13.8 billion years ago the universe was in an extremely hot, dense state**, and it has been expanding and cooling ever since. The idea grew step by step:

- **Alexander Friedmann** (1922) showed that Einstein's equations allow an expanding universe.

- **Georges Lemaître** (1927), a Belgian priest and physicist, proposed that the universe began from a "primeval atom".
- **Edwin Hubble** (1929) showed that distant galaxies are moving away from us, and the farther they are, the faster they recede.
- **George Gamow** and **Ralph Alpher** (1948) worked out how hydrogen and helium formed in the first minutes, and predicted a leftover glow of radiation.
- The name "Big Bang" was coined, half-mockingly, by Fred Hoyle in a 1949 BBC radio talk.

CLEARING A COMMON MISCONCEPTION

The Big Bang was **not an explosion at one point into empty space**. There was no "outside" for it to explode into. Space itself began stretching everywhere at once, carrying matter with it. There is therefore no centre of the universe and no edge we could travel to.

A Brief History of the Universe

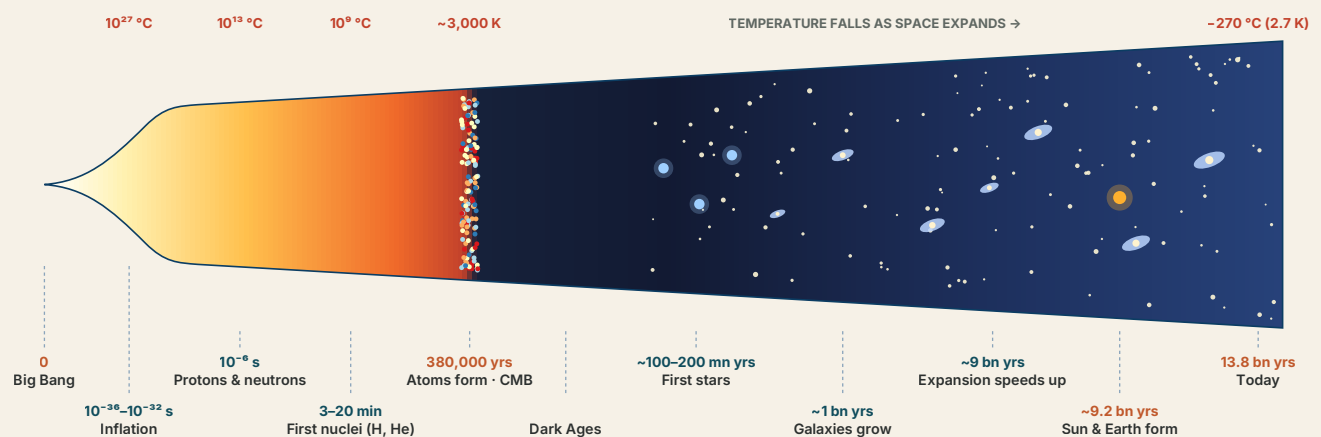


Fig. 1.2 The universe widens and cools from left to right. The early stages took tiny fractions of a second; the later ones took billions of years. Not to scale.

Stages after the Big Bang

1. **Cosmic inflation** (roughly 10^{-36} to 10^{-32} second): space ballooned by an enormous factor in a tiny fraction of a second. Inflation smoothed the universe out, and tiny quantum ripples were stretched into the seeds of future galaxies.
2. **The first particles**: as the universe cooled, quarks combined into protons and neutrons within the first second.
3. **The first nuclei** (about 3 to 20 minutes): protons and neutrons fused into the nuclei of **hydrogen** (about 75% by mass) and **helium** (about 25%), with traces of deuterium and lithium. Every heavier element came later, from stars.
4. **Atoms and the first light** (about **380,000 years**): the universe cooled to about 3,000 K, so electrons could join nuclei to form neutral atoms. Light could now travel freely for the first time. That light survives today as the **Cosmic Microwave Background**.
5. **Dark Ages and Cosmic Dawn**: no stars yet shone. The first stars lit up about 100 to 200 million years after the Big Bang, and their ultraviolet light ionised the gas around them.
6. **Galaxies** grew by gravity, pulling gas and dark matter together and merging with one another.
7. About **5 billion years ago**, dark energy began to dominate and the expansion started to **speed up**. Our Sun and Earth formed about **4.6 billion years ago**.

How might the universe end?

- **Big Freeze (heat death)**: the most widely expected outcome if dark energy stays constant. Galaxies drift apart, stars burn out and the universe grows cold and dark.

- **Big Rip:** if dark energy grows stronger, the expansion could eventually tear apart galaxies, stars and even atoms.
- **Big Crunch:** if the expansion ever reversed, everything would collapse back into a hot, dense state. A related idea, the **oscillating (cyclic) universe** proposed by Richard Tolman in the 1930s, imagines endless cycles of Big Bang and Big Crunch. Recent hints that dark energy may be weakening (Section 04) have revived interest in such possibilities.

03 Evidence for the Big Bang

1. Galaxies Are Moving Apart: Redshift

When a source of light moves away, its light waves are stretched to longer, redder wavelengths. This is **redshift**. When it approaches, the waves are squeezed towards blue, a **blueshift**. Astronomers spot the shift in the pattern of dark lines in a galaxy's spectrum. Vesto Slipher measured the first galaxy redshifts between 1912 and 1917, and in 1929 Hubble showed that redshift grows with distance. For distant galaxies the cause is not ordinary motion through space but the **stretching of space itself (cosmological redshift)**.

Redshift and Blueshift

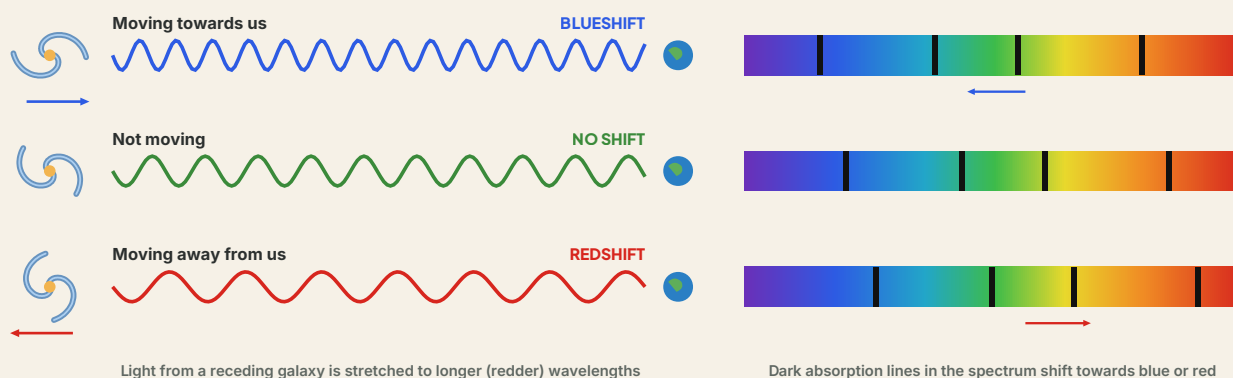


Fig. 1.3 Light from a galaxy moving away from us is stretched; the dark lines in its spectrum slide towards the red end. Almost every distant galaxy shows a redshift.

2. The Cosmic Microwave Background (CMB)

In 1965 **Arno Penzias and Robert Wilson**, working with a radio antenna at Bell Labs in the USA, found a faint microwave hiss coming equally from every direction. It turned out to be the **Cosmic Microwave Background**: the afterglow of the hot early universe, released about 380,000 years after the Big Bang and since stretched into microwaves by the expansion of space. It won them the 1978 Nobel Prize.

- The CMB is the **oldest light in the universe**, and it now has a temperature of only **2.725 K** (about -270°C).
- Its tiny hot and cold spots are the seeds from which galaxies grew. It has been mapped by NASA's **COBE** (1989; Nobel 2006), **WMAP** (2001) and ESA's **Planck** (2009).

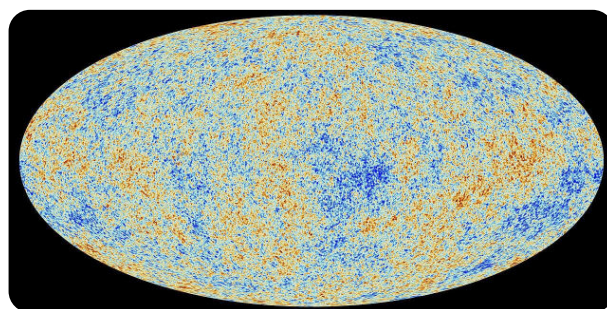


Fig. 1.4 The CMB mapped by ESA's Planck satellite. The colours show temperature differences of only about 1 part in 100,000.

3. The Mix of Light Elements

The Big Bang theory predicts that the early universe should have made about **three parts hydrogen to one part helium** by mass, plus a trace of lithium. This is what we observe in the oldest stars and gas clouds.

4. The Universe Has Changed Over Time

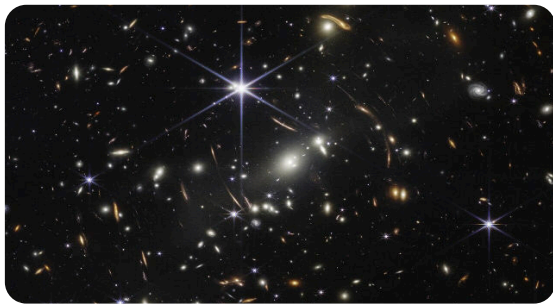


Fig. 1.5 Webb's First Deep Field (2022). Thousands of galaxies in a patch of sky the size of a grain of sand held at arm's length.

If the universe had always been the same, distant regions would look like nearby ones. They do not. Galaxies seen as they were billions of years ago are smaller, more irregular and full of young stars, and **quasars** were far commoner in the past. The James Webb Space Telescope (JWST) now sees galaxies from the first few hundred million years. The most distant confirmed so far, **MoM-z14**, is seen as it was about **280 million years** after the Big Bang (redshift 14.44, confirmed in 2025).

PRELIMS POINTER

In 2012 UPSC asked which observations are cited as evidence for the continued expansion of the universe. The answer was **detection of microwaves in space (the CMB) and the redshift of galaxies**. The movement of asteroids has nothing to do with it. Supernovae were not part of the accepted answer, though Type Ia supernovae later revealed that the expansion is accelerating.

04 Expansion, Dark Matter and Dark Energy

Hubble's Law

Hubble's law states that a galaxy's speed of recession is proportional to its distance: $v = H_0 \times d$. The constant H_0 , the **Hubble constant**, measures how fast the universe is expanding today. It is quoted in km/s per megaparsec: a value of 70 means a galaxy recedes 70 km/s faster for every extra megaparsec (3.26 million light-years) of distance. Running the expansion backwards gives the age of the universe.

The Expanding Universe and Hubble's Law

Space itself stretches: every galaxy moves away from every other

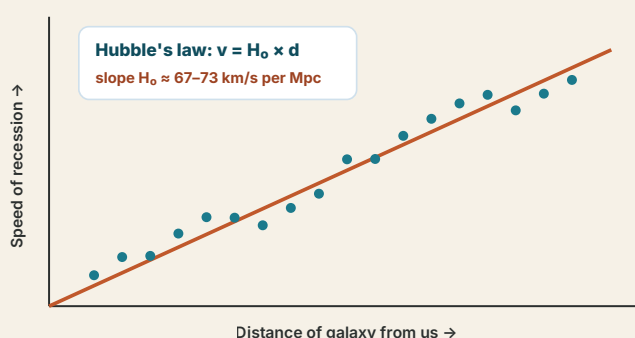
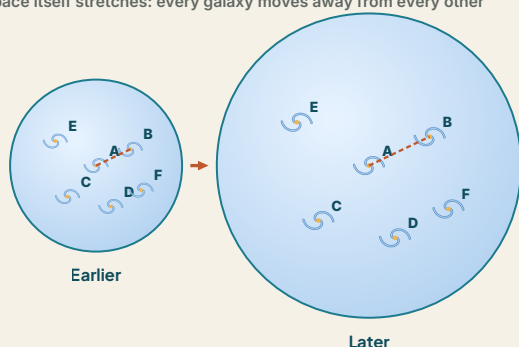


Fig. 1.6 Dots on an inflating balloon all move apart, and the farther apart two dots are, the faster their separation grows. Plotting galaxies' speed against distance gives a straight line whose slope is H_0 .

The Hubble Tension

Two families of methods give different values of H_0 . Measurements based on the early universe (the CMB) give about **67–68**. Measurements based on the nearby universe, using Cepheid stars and supernovae as distance markers, give about **73**. The gap of roughly 8% has survived years of checks, including with the JWST, and is called the **Hubble tension**. It may point to a measurement problem or to new physics. Gravitational waves from colliding neutron stars, used as "standard sirens", offer an independent way to settle it.

An Accelerating Universe and Dark Energy

Gravity should slow the expansion down. In **1998**, however, two teams studying distant **Type Ia supernovae** found that the expansion is **speeding up** (Nobel Prize 2011, Saul Perlmutter, Brian Schmidt and Adam Riess). The unknown cause is called **dark energy**: a property of space itself that pushes the universe apart. It makes up about **68%** of the universe's total energy content.

In March 2025 the **Dark Energy Spectroscopic Instrument (DESI)** in Arizona, which has built the largest 3D map of the universe (about 15 million galaxies and quasars), reported hints that **dark energy may be weakening over time**. The evidence is not yet conclusive. If confirmed, it would change our picture of how the universe will end.

Dark Matter

Dark matter is matter that neither emits, absorbs nor reflects light, so it is invisible. We know it is there only through its **gravity**. It makes up about **27%** of the universe, roughly **five times as much as ordinary matter**.

- **Fritz Zwicky** (1933) found galaxies in the Coma cluster moving too fast to be held together by their visible mass.
- **Vera Rubin** (1970s) found that stars in the outer parts of spiral galaxies orbit as fast as those near the centre. That is possible only if the galaxies sit inside huge invisible halos.
- **Gravitational lensing**: mass bends light, so galaxy clusters act as lenses that distort the galaxies behind them. The amount of bending reveals far more mass than we can see.
- Its nature is unknown. Candidates include hypothetical particles such as WIMPs and axions. ESA's **Euclid** telescope (launched 2023) is mapping dark matter across a third of the sky.

What the Universe Is Made Of, and the Hubble Tension

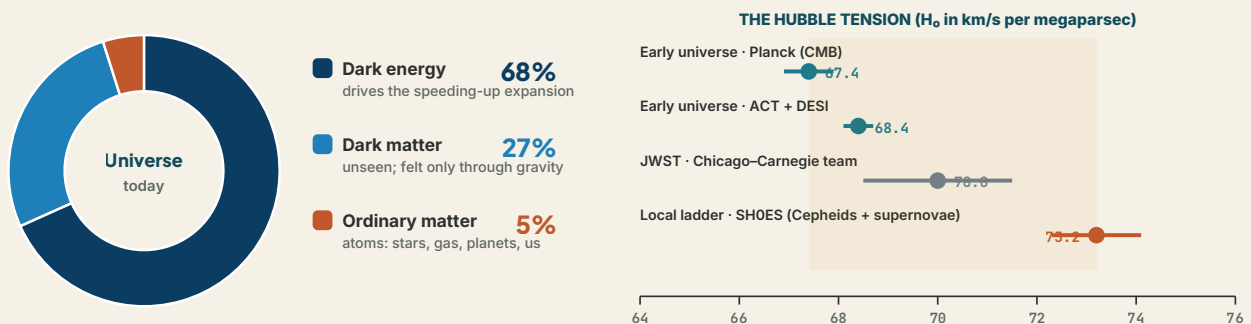


Fig. 1.7 Left: ordinary matter, everything made of atoms, is only about 5% of the universe (Planck values). Right: early-universe and nearby-universe measurements of H_0 disagree.

05 Galaxies and the Milky Way

A **galaxy** is a huge system of stars, gas, dust and dark matter held together by gravity. Galaxies range from dwarfs with a few million stars to giant ellipticals with more than a trillion. **Most large galaxies have a supermassive black hole at their centre**. Galaxies are the basic building blocks of the universe, and they gather into groups, clusters and superclusters.

Types of Galaxies

In 1926 Edwin Hubble sorted galaxies by shape into a "tuning fork" diagram. It is a classification, not an evolutionary sequence: galaxies do not move along it as they age.

Hubble's Classification of Galaxies (the "Tuning Fork")

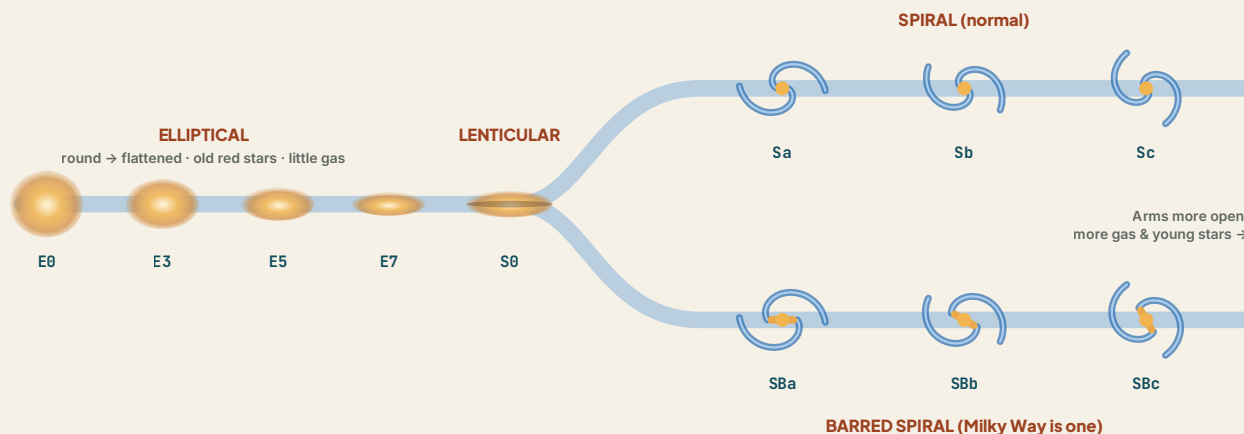


Fig. 1.8 Ellipticals (E0 to E7) grow flatter to the right. Spirals and barred spirals (a to c) have more open arms, more gas and more young stars. Irregular galaxies have no regular shape and sit outside the fork.

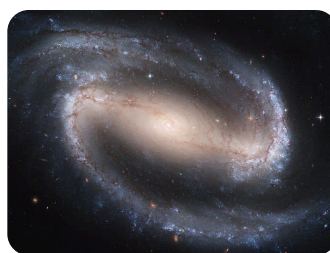
TYPE	SHAPE	STARS, GAS AND STAR BIRTH	EXAMPLES
Elliptical (E)	Smooth, round to oval; no arms	Mostly old, reddish stars; very little gas or dust, so few new stars. Include the largest galaxies	M87 (Virgo cluster)
Spiral (S)	Flat disc with spiral arms around a central bulge	Old stars in the bulge; gas, dust and young blue stars in the arms, where stars are still forming	Andromeda (M31)
Barred spiral (SB)	Spiral whose arms start from a straight bar of stars through the centre	As for spirals; the bar funnels gas inwards	Milky Way, NGC 1300
Lenticular (S0)	Disc and bulge but no arms	Little gas; mostly old stars	NGC 5866
Irregular (Irr)	No definite shape, often after a collision or pull from a neighbour	Gas-rich, with plenty of star birth	Large and Small Magellanic Clouds



Elliptical: M87, home of the first black hole ever imaged



Spiral: Andromeda, our big neighbour



Barred spiral: NGC 1300



Irregular: NGC 1427A

Our Galaxy: The Milky Way

On a dark night the **Milky Way**, called **Akash Ganga** in India, appears as a hazy band across the sky. It is our view of the galaxy's disc from inside it.

- It is a **barred spiral galaxy** with about **100–400 billion stars**. The disc is about **1 lakh light-years** across but only about 1,000 light-years thick.
- The Sun lies in a minor arm, the **Orion Arm (Orion Spur)**, about **26,000 light-years** from the centre.
- The Sun orbits the centre at about **230 km/s** and takes about **230 million years** per lap (a "galactic year").
- At the centre lies **Sagittarius A***, a supermassive black hole of about **4 million Suns**, photographed in 2022.

- Its two bright satellite galaxies, the **Large and Small Magellanic Clouds**, are visible only from the southern hemisphere.

Structure of the Milky Way

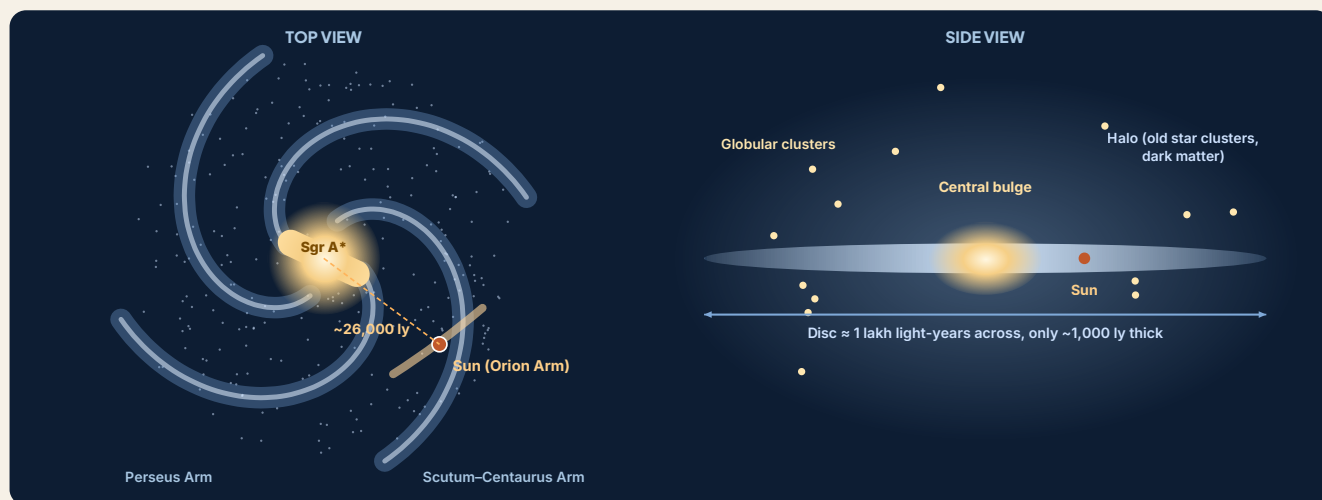


Fig. 1.9 From above, the Milky Way is a barred spiral with major arms. From the side, it is a thin disc with a central bulge, surrounded by a halo of old star clusters and dark matter.

The Local Group and Beyond

- The Milky Way belongs to the **Local Group**, more than 80 galaxies spread over about 10 million light-years. Its biggest members are **Andromeda**, the Milky Way and Triangulum.
- **Andromeda (M31)** is about **2.5 million light-years** away and is the most distant object easily visible to the naked eye. It is approaching at about 110 km/s. A collision has long been forecast for about 4–5 billion years from now, but a 2025 study using Gaia and Hubble data put the chance of a merger within the next 10 billion years at only about 50%.
- The Local Group lies on the edge of the Virgo Cluster, part of the **Laniakea Supercluster** (mapped in 2014, about 1 lakh galaxies across 520 million light-years). On the largest scales galaxies form a **cosmic web** of filaments and walls around vast empty voids.
- **Quasars** are the brilliant cores of distant young galaxies, powered by gas swirling into a supermassive black hole. A single quasar can outshine its whole galaxy.

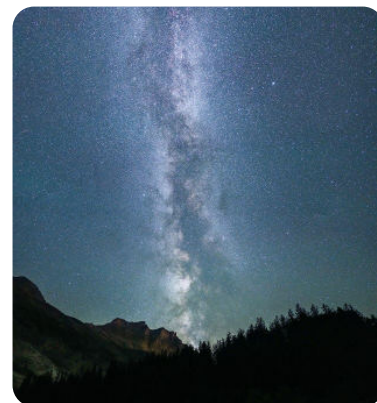


Fig. 1.10 The Milky Way rising over the Alps: we see our own galaxy edge-on, from inside its disc.

IN THE NEWS · INDIA CONNECT

Alaknanda galaxy (2025): astronomers at the **National Centre for Radio Astrophysics (NCRA-TIFR), Pune**, used JWST images to find a well-formed, Milky Way-like spiral galaxy seen as it was only about **1.5 billion years** after the Big Bang (redshift about 4). Named after the Himalayan river, it has two clear spiral arms and forms stars about 20 times faster than the Milky Way. Such an orderly spiral so early challenges models that expected young galaxies to be clumpy and chaotic.

A **star** is a huge, glowing ball of hot gas (plasma) that makes its own energy by **nuclear fusion**. In the Sun's core, at about **15 million °C**, hydrogen nuclei fuse into helium, and a little mass is turned into a great deal of energy ($E = mc^2$). A

star's life is a balance: gravity pulls inwards, while the pressure of hot gas and radiation from fusion pushes outwards. When the fuel changes, the balance shifts and the star changes.

Mass decides almost everything: a star's temperature, colour, brightness, lifespan and fate. A heavier star has a hotter core and burns its fuel far faster, so it lives a shorter life. The Sun will shine for about 10 billion years in all. A star of ten Suns lasts only some tens of millions of years, while a small red dwarf can last trillions. This is why, as UPSC tested in 2024, giant stars live shorter lives than dwarf stars, because their nuclear reactions run much faster.

Colour, Temperature and the H-R Diagram

A star's colour shows its surface temperature: **blue stars are the hottest, red stars the coolest**, and the Sun, a yellow star, lies in between. Brightness is measured as **magnitude**: on this scale a lower number means a brighter star.

Apparent magnitude is how bright a star looks from Earth; **absolute magnitude** is how bright it would look from a standard distance. The **Hertzsprung–Russell (H-R) diagram** plots stars by temperature and true brightness, and it sorts them into clear groups.

The Hertzsprung–Russell Diagram

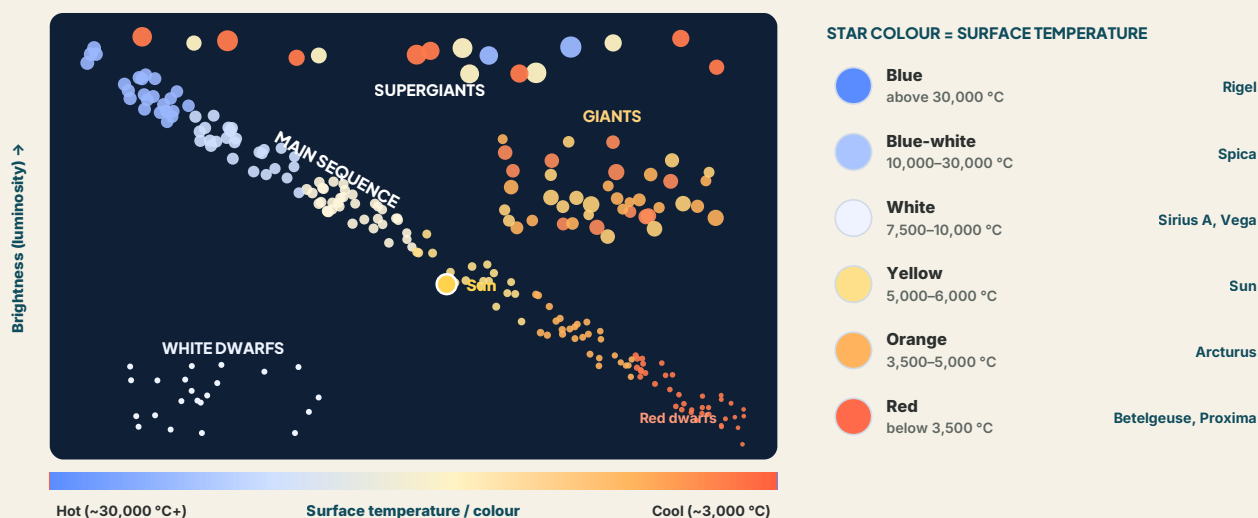


Fig. 1.11 About 90% of stars, including the Sun, lie on the main sequence, burning hydrogen in their cores. Giants and supergiants are ageing stars; white dwarfs are dead stellar cores.

Birth of a Star

- 1. Nebula:** stars are born in cold, dense clouds of gas (mostly hydrogen) and dust, called nebulae or molecular clouds.
- 2. Collapse:** a disturbance, such as the shock wave from a nearby supernova, makes part of a cloud collapse under its own gravity.
- 3. Protostar:** the collapsing core heats up as it shrinks, but it is not yet hot enough for fusion. It glows from the heat of contraction and is hidden by dust. Young stars in this stage, called **T Tauri stars**, blow strong winds.
- 4. Main-sequence star:** when the core reaches about **10 million °C**, hydrogen fusion begins, and the outward push of energy halts the collapse. A star is born.

Objects below about **8% of the Sun's mass** (about 80 Jupiters) never become hot enough to fuse hydrogen. These "failed stars" are **brown dwarfs**.

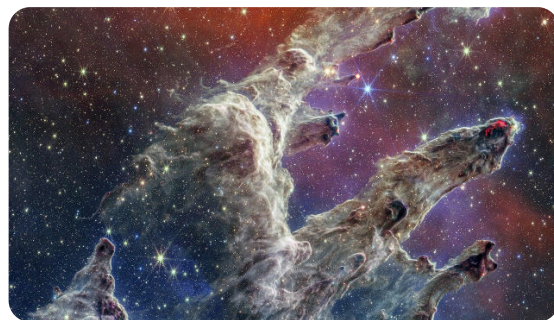


Fig. 1.12 "Pillars of Creation", Eagle Nebula (JWST): a stellar nursery.

Red dwarfs are the smallest true stars: cool, dim and extremely long-lived. They make up about **three-quarters** of the stars in the **Milky Way**, yet none is visible to the naked eye. **Proxima Centauri**, the nearest star to the Sun, is a red dwarf.

The Life Cycle of Stars

Two Paths: How Stars Live and Die

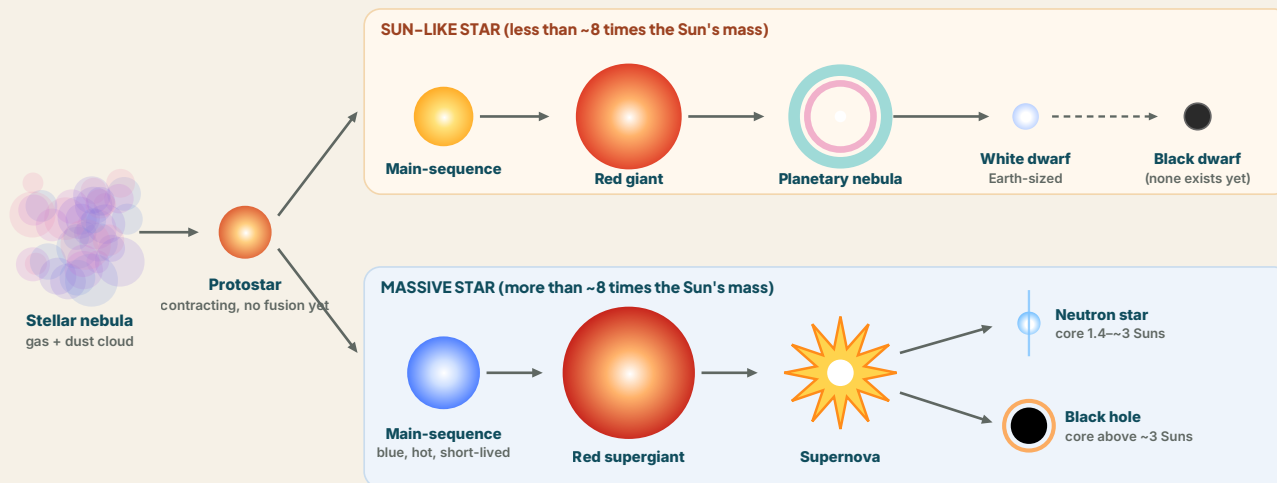


Fig. 1.13 A star's starting mass decides its path. Sun-like stars end quietly as white dwarfs; massive stars explode as supernovae and leave behind neutron stars or black holes.

Sun-like stars (up to about 8 times the Sun's mass)

- **Red giant:** when the hydrogen in the core runs out, the core shrinks and heats up while the outer layers swell enormously and cool. In about 5 billion years the Sun will swell into a red giant, swallowing Mercury and Venus, and possibly the Earth. The core then fuses helium into carbon and oxygen.
- **Planetary nebula:** the outer layers drift away as a glowing shell of gas. The name is misleading: it has nothing to do with planets, and early telescopes simply showed it as a round, planet-like disc.
- **White dwarf:** the exposed core, about the size of the Earth but with roughly half the Sun's mass. A teaspoonful would weigh several tonnes. It shines only from stored heat.
- **Black dwarf:** a white dwarf that has cooled completely. This takes far longer than the present age of the universe, so **no black dwarf exists yet**.

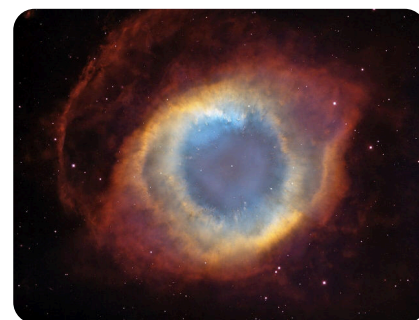


Fig. 1.14 The Helix Nebula: a planetary nebula, the cast-off outer layers of a dying Sun-like star.

CHANDRASEKHAR LIMIT

In 1930, at the age of 19, **Subrahmanyan Chandrasekhar** calculated that a white dwarf cannot be heavier than about **1.4 times the Sun's mass**. Above this limit nothing can hold up its weight, and it collapses into a neutron star or a black hole. He shared the 1983 Nobel Prize in Physics, and NASA's **Chandra X-ray Observatory** (1999) is named after him.

Massive stars (more than about 8 times the Sun's mass)

- **Red supergiant:** a massive star swells far beyond a red giant. **Betelgeuse** in Orion is one. Its core fuses ever-heavier elements in layers, like an onion, ending with **iron**.

- **Supernova:** fusing iron uses up energy instead of releasing it, so the core collapses in under a second and rebounds in a titanic explosion. For weeks a supernova can outshine an entire galaxy.
- What remains depends on the mass of the collapsed core: a **neutron star** (about 1.4 to 3 Suns) or a **black hole** (above about 3 Suns).

FEATURE	NOVA	TYPE IA SUPERNOVA	TYPE II SUPERNOVA
Which star	White dwarf in a close pair (binary)	White dwarf in a binary	Single massive star (over ~8 Suns)
What happens	Hydrogen pulled from the partner piles up on the surface and ignites in a flash	The white dwarf gains mass up to the Chandrasekhar limit, and runaway fusion blows it apart	The iron core collapses and the outer layers are blasted away
Does the star survive?	Yes; it can erupt again and again	No; nothing is left	The core survives as a neutron star or black hole
Why it matters	T Coronae Borealis, a recurring nova last seen in 1946, is awaited by astronomers to flare again	Peak brightness is almost the same every time, so they are "standard candles" for measuring distance; they revealed the accelerating universe	Scatters heavy elements into space; e.g. the 1054 CE supernova that left the Crab Nebula



Fig. 1.15 The Crab Nebula: debris of a supernova recorded by Chinese astronomers in 1054 CE. A pulsar spinning 30 times a second lies at its heart.

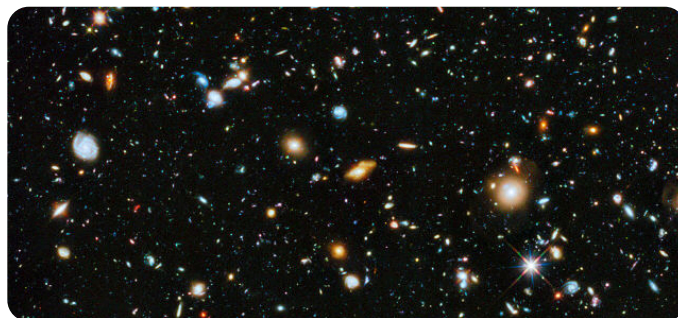


Fig. 1.16 The Hubble Ultra Deep Field: almost every point of light here is a galaxy, each with billions of stars living and dying.

We Are Made of Star Stuff

The Big Bang made only hydrogen, helium and a trace of lithium. Everything else was forged later, by **stellar nucleosynthesis**:

- stars fuse light elements into heavier ones, such as carbon, oxygen, silicon and iron, in their cores;
- elements **heavier than iron**, such as gold, platinum and uranium, are made mainly in **supernovae and collisions of neutron stars** (kilonovae);
- these explosions scatter the elements into space, where they enrich the clouds from which new stars and planets form. The calcium in our bones and the iron in our blood were made inside stars.

Cepheid variables are pulsating stars that brighten and dim with a regular period. In 1912 **Henrietta Leavitt** found that the longer the period, the brighter the star. Comparing a Cepheid's true brightness with how bright it looks gives its distance. Hubble used Cepheids in 1923–24 to prove that Andromeda is a separate galaxy far beyond the Milky Way.

87 Black Holes and Gravitational Waves

Neutron Stars and Pulsars

A **neutron star** is the collapsed core left by a supernova. The crushing gravity forces protons and electrons together into neutrons. About **20 km across** yet heavier than the Sun, it is so dense that a teaspoonful would weigh about a

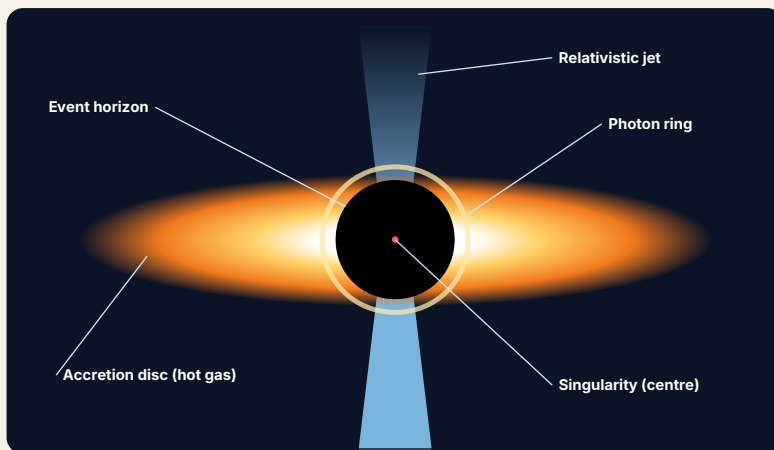
billion tonnes. **Pulsars** are spinning neutron stars that sweep beams of radio waves across space like a lighthouse. They were discovered in 1967 by **Jocelyn Bell Burnell**. Their pulses are so regular that pulsars serve as cosmic clocks. **Magnetars** are neutron stars with the strongest magnetic fields known.

Black Holes

A **black hole** is a region where matter is packed so tightly that gravity lets nothing escape, **not even light**. As UPSC asked in 2000, this property comes from its **extremely high density**, not its size.

- **Event horizon**: the boundary of no return. Its radius is the **Schwarzschild radius**, named after Karl Schwarzschild, who worked it out in 1916.
- **Singularity**: the centre, where present-day physics breaks down.
- **Accretion disc and jets**: gas spiralling in is heated to millions of degrees and glows in X-rays. Some is flung out as jets at nearly the speed of light, which makes black holes detectable.
- **Types**: **stellar-mass** (a few to about 100 Suns, from dead massive stars), **intermediate** (rare), and **supermassive** (millions to billions of Suns, at the centres of galaxies).
- In 1974 **Stephen Hawking** showed theoretically that black holes should slowly leak energy (**Hawking radiation**).

Anatomy of a Black Hole



HOW SMALL WOULD THEY BE?

Event-horizon (Schwarzschild) radius if squeezed

	Earth ≈ 9 mm · a marble
	Sun ≈ 3 km · a small town
	Sgr A* (4 million Suns) ≈ 12 million km · fits inside Mercury's orbit
	M87* (6.5 billion Suns) ≈ 19 billion km · wider than Neptune's orbit

Fig. 1.17 Left: the main parts of an active black hole. Right: how small an object would have to be squeezed to become a black hole.

First images of black holes

The **Event Horizon Telescope (EHT)** links radio dishes across the globe so that they work as one Earth-sized telescope. It has photographed two black holes:

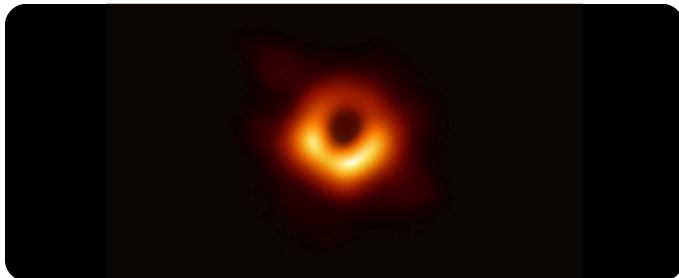


Fig. 1.18 M87* (April 2019): the first image of a black hole, 6.5 billion Suns, 55 million light-years away.

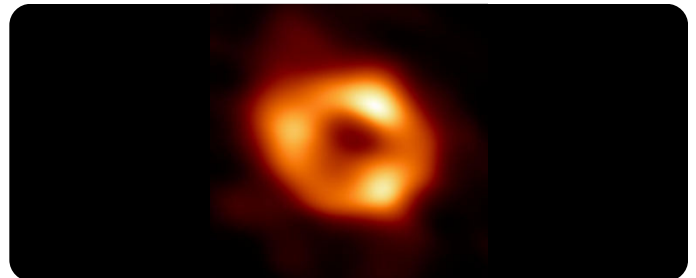


Fig. 1.19 Sagittarius A* (May 2022): the Milky Way's own central black hole, 4 million Suns, 27,000 light-years away.

The bright ring is hot gas whose light is bent around the black hole; the dark centre is its "shadow".

Gravitational Waves

Einstein's general theory of relativity (1915) describes gravity as the bending of **spacetime** by mass. In 1916 he predicted that violently accelerating masses, such as two black holes spiralling together, would send **gravitational waves** rippling outwards at the speed of light. These waves stretch and squeeze space itself as they pass.

- **First direct detection: 14 September 2015**, by the twin **LIGO** detectors in the USA. The signal (GW150914) came from two black holes of about 36 and 29 Suns merging 1.3 billion light-years away. It won the **2017 Nobel Prize** (Rainer Weiss, Barry Barish, Kip Thorne).
- **GW170817** (2017): a collision of two neutron stars was seen both in gravitational waves and in light. This launched **multi-messenger astronomy** and confirmed that such collisions forge gold and platinum.
- By early 2026 the global network had confirmed **more than 200** detections over four observing runs. The clearest signal yet, **GW250114** (January 2025), confirmed Stephen Hawking's prediction that the area of a black hole's event horizon can never shrink.
- Gravitational waves let us observe events that give out no light, test Einstein's theory in extreme conditions and measure the expansion of the universe independently.

How LIGO Catches a Gravitational Wave

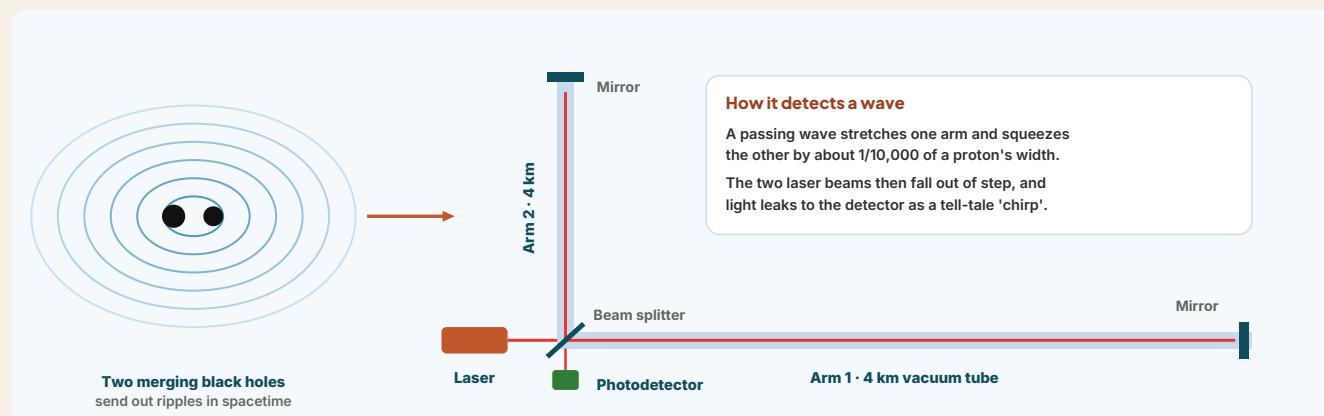


Fig. 1.20 A laser interferometer compares the lengths of two long, perpendicular arms. A passing wave changes them by an amount far smaller than an atomic nucleus.

Detectors today: LIGO Hanford and Livingston (USA), Virgo (Italy), KAGRA (Japan, built underground) and GEO600 (Germany). **LISA**, a space-based detector of three spacecraft about 2.5 million km apart, was adopted by ESA (with NASA) in 2024 for launch around 2035. Its earlier version, **eLISA**, appeared in UPSC Prelims 2017.

Einstein's theory also predicts that **light is bent by gravity** (first confirmed during the 1919 solar eclipse), that **matter warps the spacetime around it**, and that **the universe is expanding**. All three were the answer to a 2018 Prelims question. Clocks also run slower in stronger gravity, which is why GPS satellites must correct their clocks by about 38 microseconds a day.

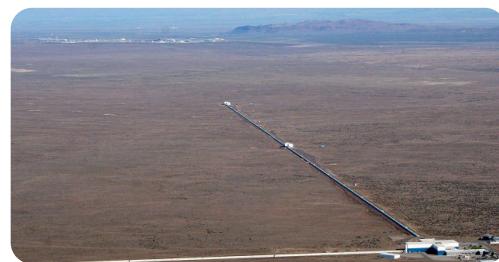


Fig. 1.21 LIGO Hanford, USA.

INDIA CONNECT · LIGO-INDIA

- **Where:** Aundha, Hingoli district, **Maharashtra**, chosen for its low seismic disturbance.
- **What:** an advanced LIGO detector with two 4-km arms, built by the **Department of Atomic Energy** and the **Department of Science and Technology** with the US National Science Foundation. The Union Cabinet approved it in April 2023 at about **₹2,600 crore**.
- **Status:** ground was broken on **23 April 2026**; first observations are targeted around **2030**. As the fifth large detector in the network, far from the others, it will greatly sharpen the pinpointing of sources in the sky.

- Indian astronomers also run the **Indian Pulsar Timing Array (InPTA)**, using the upgraded GMRT. In 2023 it joined international teams in reporting evidence of a background of very low-frequency gravitational waves, probably from pairs of supermassive black holes.

08 Constellations and the Pole Star

A **constellation** is a group of stars that forms a recognisable pattern as seen from Earth. The International Astronomical Union recognises **88 constellations**, which together divide up the whole sky. The stars of a constellation usually lie at very different distances and are not physically linked. A smaller pattern within a constellation, such as the Big Dipper, is an **asterism**. Because the Earth rotates from west to east, the stars appear to rise in the east, wheel across the sky and set in the west. Indian astronomy divides the Moon's path into **27 nakshatras**.

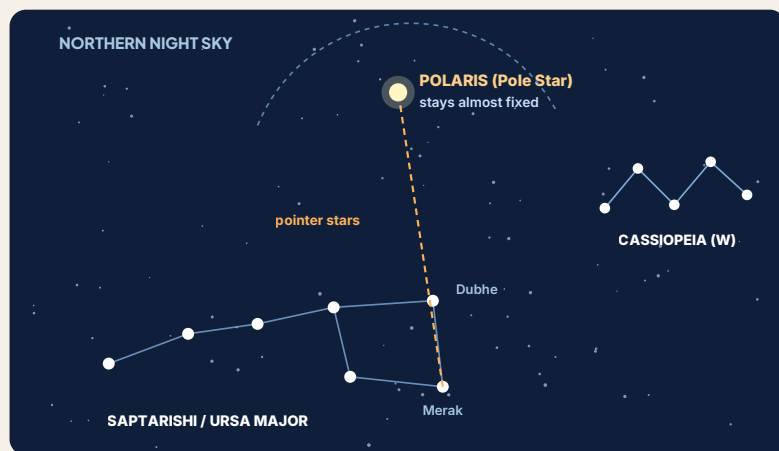
- Ursa Major (Great Bear)**, known in India as the **Saptarishi**: seven bright stars form the Big Dipper, and its two "pointer stars" lead to the Pole Star.
- Orion (the Hunter)**: easy to spot on winter evenings by its belt of three stars. It holds **Betelgeuse** (a red supergiant) and **Rigel** (a blue supergiant). Following the belt leads to **Sirius**, the brightest star in the night sky.
- Cassiopeia**: a W- or M-shaped group on the opposite side of the Pole Star from the Saptarishi.
- Crux (the Southern Cross)**: used to find south in the southern hemisphere, where the Pole Star cannot be seen.

The Pole Star (Polaris)

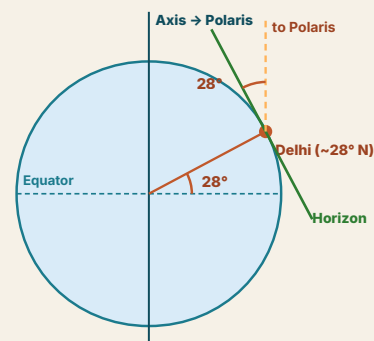
Polaris, the last star in the tail of the Little Bear (Ursa Minor), lies almost exactly above the Earth's North Pole, in line with the Earth's axis. So while every other star appears to circle around it, **Polaris seems to stay fixed**, and it always marks true north. It is visible only from the northern hemisphere.

- The angle of Polaris above the horizon is **equal to the observer's latitude**: about 28° at Delhi, 0° (on the horizon) at the Equator and 90° (overhead) at the North Pole.
- Seen from the **Equator**, stars rise and set at right angles to the horizon. At the **poles** they circle parallel to the horizon and never set.
- The Earth's axis slowly wobbles in a cycle of about **26,000 years (precession)**, so the pole star changes: Thuban was the pole star about 3000 BCE, and **Vega** will be near the pole around 14,000 CE.

Finding the Pole Star, and Why It Tells You Your Latitude



ALTITUDE OF POLE STAR = YOUR LATITUDE



At the Equator Polaris sits on the horizon; at the North Pole it is overhead

Fig. 1.22 Extend the line through the two pointer stars of the Saptarishi to reach Polaris. Because Polaris lies on the line of the Earth's axis, its height above the horizon equals your latitude.

UPSC 2012 asked how a person lost in a desert at night could walk to a village due east using the Pole Star. Facing Polaris means facing north, so to walk east one keeps the **Pole Star on the left**.

Observing the Universe: Telescopes and India's Role

The Earth's atmosphere blocks most of the radiation arriving from space. Only **visible light**, some infrared and most **radio waves** reach the ground. This is why gamma-ray, X-ray, ultraviolet and most infrared telescopes must be placed in space, while optical and radio telescopes can work from high, dry, dark mountain sites.

Atmospheric Windows: Which Telescopes Can Work From the Ground?

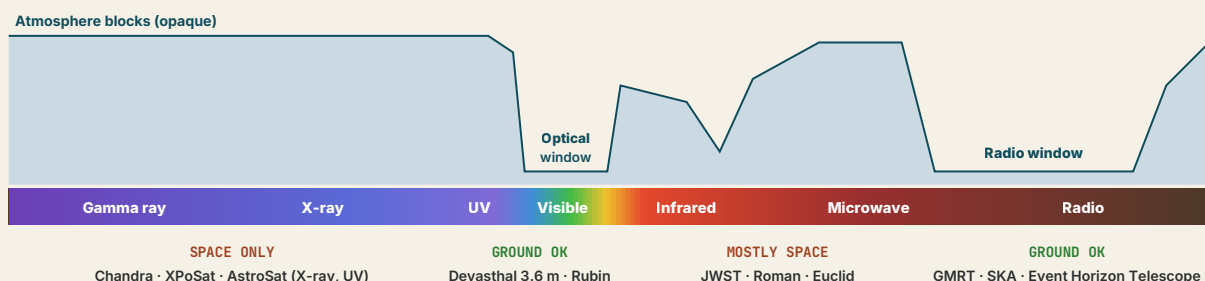


Fig. 1.23 The shaded curve shows how strongly the atmosphere blocks each kind of radiation. Only the optical and radio "windows" reach the ground.

The major observatories, in space and on the ground, are:

OBSERVATORY	WHO / WHEN	WAVEBAND AND LOCATION	KNOWN FOR
Hubble Space Telescope	NASA-ESA, 1990	Visible, ultraviolet; low Earth orbit	Deep fields; measuring the expansion rate
Chandra X-ray Observatory	NASA, 1999	X-ray; high Earth orbit	Black holes, supernova remnants; named after S. Chandrasekhar
James Webb Space Telescope	NASA-ESA-CSA, launched 25 Dec 2021	Infrared; 6.5 m gold-coated mirror; orbits the Sun at the L2 point, ~15 lakh km from Earth	The earliest galaxies; atmospheres of exoplanets
Euclid	ESA, 2023	Visible and near-infrared; L2	3D map of dark matter and dark energy
Nancy Grace Roman Space Telescope	NASA, launched 30 Aug 2026	Wide-field infrared; travelling to L2; first images expected early 2027	Dark energy; expected to find about 1 lakh exoplanets
Vera C. Rubin Observatory	USA; Cerro Pachón, Chile; first images June 2025	Optical; 3,200-megapixel camera, the largest digital camera ever built	Ten-year Legacy Survey of Space and Time
Square Kilometre Array (SKA)	Intergovernmental (SKAO); HQ in the UK	Radio; antennas in South Africa and Australia	Will be the world's largest radio telescope; India is a member country
Event Horizon Telescope	Global collaboration	Radio; dishes on several continents linked together	The first images of black holes

India's Windows on the Universe

- **AstroSat** (launched **28 September 2015** by PSLV-C30): India's first dedicated multi-wavelength space observatory, observing in ultraviolet, optical and X-ray at once. It weighs about 1,500 kg and orbits at about 650 km. Both statements in UPSC's 2016 question (that only the USA and Russia had launched similar observatories, and the 2,000 kg / 1,650 km figures) were therefore wrong.

- **XPoSat** (launched **1 January 2024** by PSLV-C58): India's first, and the world's second (after NASA's IXPE), mission to study the **polarisation of X-rays** from black holes, neutron stars and pulsars.
- **GMRT** (Giant Metrewave Radio Telescope), at **Khodad near Pune**: 30 dishes, each 45 m wide, run by NCRA-TIFR. It is one of the world's most sensitive low-frequency radio telescopes, upgraded as uGMRT.
- **Devasthal Optical Telescope** (3.6 m), run by ARIES at Nainital, Uttarakhand (2016): India's largest optical telescope. The International Liquid Mirror Telescope (first light 2022) stands beside it.
- **Hanle, Ladakh**: home of the Indian Astronomical Observatory and the **MACE** gamma-ray telescope (2024), the largest of its kind in Asia, at about 4,300 m. Hanle is also **India's first Dark Sky Reserve** (2022).
- India is a partner in the **SKA** and the **Thirty Meter Telescope**, and is building **LIGO-India**. **Aditya-L1**, India's solar observatory, is covered in the next chapter.



Fig. 1.24 The Vera C. Rubin Observatory on Cerro Pachón in Chile, a high and dry site with dark skies.

Planets Beyond the Solar System

An **exoplanet** is a planet orbiting a star other than the Sun. The first one found around a Sun-like star, **51 Pegasi b** (1995), earned the 2019 Nobel Prize. NASA's count of confirmed exoplanets passed **6,000 in September 2025**. Most are found by the **transit method**, which detects the tiny dip in a star's light as a planet passes in front (Kepler, TESS), or the **radial-velocity method**, which detects the star's slight wobble. Planets in the **habitable or "Goldilocks" zone** orbit at a distance where liquid water could exist on the surface.

USING THIS CHAPTER IN MAINS

GS Paper I seldom asks about cosmology directly, but GS Paper III often asks about space science: gravitational waves, black-hole imaging, space observatories and India's role. A good answer:

- defines the concept in two crisp lines and adds a quick labelled diagram (a stellar life cycle, a LIGO interferometer or the composition of the universe);
- quotes current facts: LIGO-India's ground-breaking in 2026, more than 200 gravitational-wave detections, the DESI hints on dark energy, more than 6,000 exoplanets;
- brings in India: AstroSat, XPoSat, GMRT, SKA membership, LIGO-India, and the Alaknanda galaxy found by NCRA scientists;
- closes with significance for fundamental physics, technology spin-offs (precision optics, lasers, data science) and scientific diplomacy.



Previous Year Questions

2024

Consider the following statements:

Statement-I: Giant stars live much longer than dwarf stars.

Statement-II: Compared to dwarf stars, giant stars have a greater rate of nuclear reactions.

Which one of the following is correct in respect of the above statements?

- ☐ a Both Statement-I and Statement-II are correct and Statement-II explains Statement-I
- ☐ b Both Statement-I and Statement-II are correct, but Statement-II does not explain Statement-I
- ☐ c Statement-I is correct, but Statement-II is incorrect
- ☒ d Statement-I is incorrect, but Statement-II is correct

Answer: (d). Giant stars burn their fuel much faster, so they live much shorter lives.

2023

Consider the following pairs:

Objects in space : Description

1. Cepheids : Giant clouds of dust and gas in space
2. Nebulae : Stars which brighten and dim periodically
3. Pulsars : Neutron stars that are formed when massive stars run out of fuel and collapse

How many of the above pairs are correctly matched?

- ☒ a Only one
- ☐ b Only two
- ☐ c All three
- ☐ d None

Answer: (a). The first two descriptions are swapped; only pair 3 is correct.

2021

Which one of the following is a reason why astronomical distances are measured in light-years?

- ☐ a Distances among stellar bodies do not change
- ☐ b Gravity of stellar bodies does not change
- ☐ c Light always travels in straight line
- ☒ d Speed of light is always same

Answer: (d). The constant speed of light makes the light-year a reliable unit of distance.

2019

Recently, scientists observed the merger of giant 'blackholes' billions of light-years away from the Earth. What is the significance of this observation?

- ☐ a 'Higgs boson particles' were detected.
- ☒ b 'Gravitational waves' were detected.
- ☐ c Possibility of inter-galactic space travel through 'wormhole' was confirmed.
- ☐ d It enabled the scientists to understand 'singularity'.

Answer: (b). Merging black holes produce gravitational waves, first detected by LIGO.

2018

Consider the following phenomena:

1. Light is affected by gravity.
2. The Universe is constantly expanding.
3. Matter warps its surrounding space-time.

Which of the above is/are the prediction/predictions of Albert Einstein's General Theory of Relativity, often discussed in media?

a 1 and 2 only

b 3 only

c 1 and 3 only

d 1, 2 and 3

Answer: (d). All three follow from general relativity.

2017

What is the purpose of 'evolved Laser Interferometer Space Antenna (eLISA)' project?

a To detect neutrinos

b To detect gravitational waves

c To detect the effectiveness of missile defence system

d To study the effect of solar flares on our communication systems

Answer: (b). It is a planned space-based gravitational-wave detector, now called LISA.

2016

With reference to 'Astrosat', the astronomical observatory launched by India, which of the following statements is/are correct?

1. Other than USA and Russia, India is the only country to have launched a similar observatory into space.
2. Astrosat is a 2000 kg satellite placed in an orbit at 1650 km above the surface of the Earth.

a 1 only

b 2 only

c Both 1 and 2

d Neither 1 nor 2

Answer: (d). Europe and Japan had also launched such observatories; AstroSat weighs about 1,500 kg and orbits at about 650 km.

2012

Which of the following is/are cited by the scientists as evidence/evidences for the continued expansion of universe?

1. Detection of microwaves in space
2. Observation of redshift phenomenon in space
3. Movement of asteroids in space
4. Occurrence of supernova explosions in space

a 1 and 2

b 2 only

c 1, 3 and 4

d None of the above can be cited as evidence

Answer: (a). The CMB and the redshift of galaxies.

2012

A person stood alone in a desert on a dark night and wanted to reach his village which was situated 5 km east of the point where he was standing. He had no instruments to find the direction but he located the polestar. The most convenient way now to reach his village is to walk in the

☐ a direction facing the polestar

☐ b direction opposite to the polestar

☒ c direction keeping the polestar to his left

☐ d direction keeping the polestar to his right

Answer: (c). The Pole Star marks north; walking east keeps north on the left.

2001

Who is the scientist in whose honour the 'Chandra' X-ray telescope has been named?

☐ a Chandrasekhara Venkata Raman

☐ b Jagadish Chandra Bose

☐ c Prafulla Chandra Roy

☒ d Subrahmanyan Chandrasekhar

Answer: (d). S. Chandrasekhar, of the Chandrasekhar limit.

2000

A 'black hole' is a body in space which does not allow any radiation to come out. This property is due to its

☐ a very small size

☐ b very large size

☒ c very high density

☐ d very low density

Answer: (c). Extreme density produces gravity strong enough to trap light.

LOTUSARISE IAS

PHYSICAL GEOGRAPHY

PRELIMS · GS PAPER I

Thunderstorms, Tornadoes and Tropical Cyclones

The atmosphere's most violent weather is driven by one simple engine: warm, moist air rising, cooling and giving up the heat it took in when its water evaporated. In a single thunderstorm that engine runs for half an hour over a few kilometres. Organised over a warm ocean, it can run for a week and spin up a cyclone hundreds of kilometres wide. India meets both: lightning is now its deadliest natural hazard, and its eastern coast faces some of the world's most destructive cyclones and storm surges.

SYLLABUS

PRELIMS

Physical Geography of India and the World: thunderstorms, lightning, tornadoes, tropical cyclones; current events (named cyclones, warning systems, notified disasters)

MAINS · GS PAPER I

Important geophysical phenomena such as cyclones; changes in critical geographical features; GS Paper III: Disaster and disaster management

CONTENTS

01 Thunderstorms: Ingredients and Life Cycle	02 Types of Thunderstorms
03 Lightning and Thunder	04 Hail, Cloudbursts and India's Local Storms
05 Tornadoes and Waterspouts	06 Cyclones and Anticyclones: The Basics
07 Tropical Cyclones: Conditions for Formation	08 Where Tropical Cyclones Form
09 Life Cycle and Structure of a Cyclone	10 Movement, Landfall and Hazards
11 Measuring and Naming Cyclones	12 Cyclones of the North Indian Ocean
13 Managing Cyclones in a Warming World	14 Previous Year Questions

This chapter covers:

- what a thunderstorm needs, its three stages, its types from single cells to supercells, and the downbursts, hail and lightning it produces;
- lightning deaths in India and the 2026 decision to notify lightning as a disaster; cloudbursts, dust storms, Kalbaisakhi and mango showers;
- how tornadoes form, how they are rated, and why most of them strike the Great Plains of the USA;
- the conditions that breed tropical cyclones, where they form and why none form at the equator or in the South Atlantic;
- the structure of a cyclone (eye, eyewall, rain bands), its movement and recurvature, storm surge and rapid intensification;
- the IMD and Saffir–Simpson scales, how cyclones are named, the Bay of Bengal and Arabian Sea compared, India's major cyclones up to 2025–26, cyclone management and climate change.

The next chapter takes up air masses, fronts and temperate cyclones.

Thunderstorms: Ingredients and Life Cycle

Thunderstorms, tornadoes and dust storms are **severe local storms**: short-lived, violent and confined to a small area, all driven by rapid upward movement of air. A **thunderstorm** is a storm produced by a **cumulonimbus** cloud, with lightning and thunder and usually heavy rain, strong gusts and sometimes hail. Around **1,800 to 2,000 thunderstorms** are active over the globe at any moment, some 16 million a year, and the planet sees roughly 40 to 50 lightning flashes every second.

They are commonest where heat and moisture are plentiful: over tropical land, in the afternoon and in the warm season. Equatorial places such as Bogor in Java and Kampala in Uganda have thunder on well over 100 days a year. Storms are fewer over the open ocean, which warms little during the day, and rare near the poles, where the air is too cold to hold much moisture.

Three Ingredients

- **Moisture**: a deep layer of humid air near the ground. When its vapour condenses it releases **latent heat**, the fuel of every storm in this chapter.
- **Instability**: air that, once nudged upwards, stays warmer than its surroundings and keeps rising. This happens when temperature falls steeply with height (Chapter 18).
- **Lift**: something to start the rise. Strong surface heating, a cold front, a mountain slope or converging winds can all do it. These triggers give convective, frontal and orographic thunderstorms.



Fig. 20.1 A cumulonimbus with a flat anvil top over Warsaw. The anvil spreads where rising air meets the stable tropopause.

The Life Cycle of a Thunderstorm Cell

Three Stages of a Thunderstorm Cell

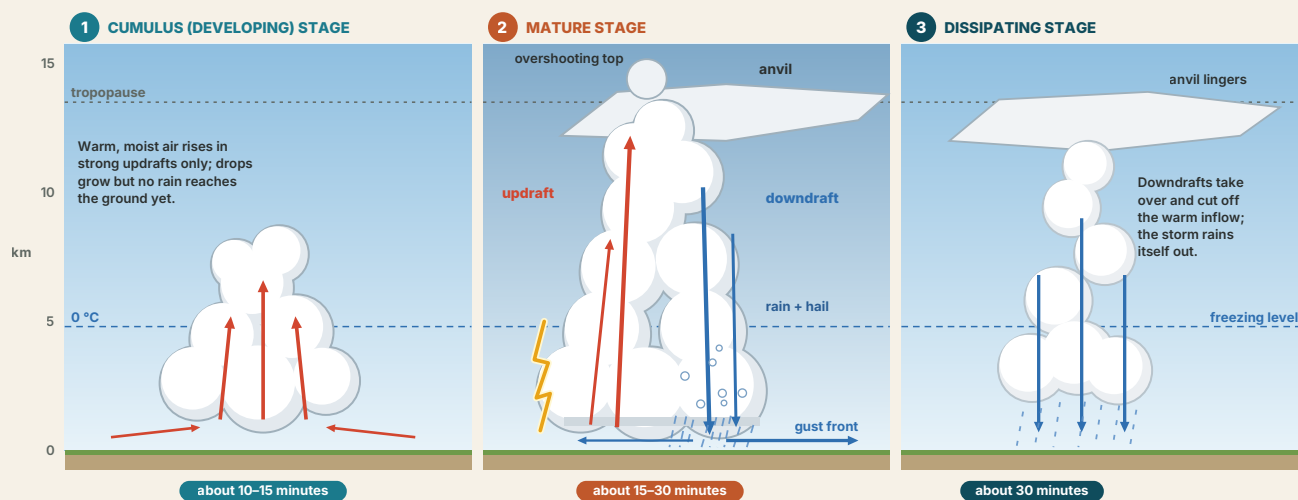


Fig. 20.2 A single cell lives for about an hour. Updrafts build it, rain-dragged downdrafts make it mature, and when the downdrafts take over the whole cloud they kill it.

1. **Cumulus (developing) stage**: rising thermals build a cumulus tower. The cloud contains **only updrafts**. Latent heat released by condensation warms the rising air, so it rises faster still. Drops grow, but there is little or no rain at the ground.
2. **Mature stage**: the tower rises above the freezing level and becomes a cumulonimbus. Falling rain and hail drag air down with them and evaporation chills it, creating **downdrafts beside the updrafts**. This is the most violent phase: heavy rain, hail, lightning, and a cold **gust front** that spreads out along the ground and announces the storm. When

the top reaches the stable tropopause it spreads into a flat **anvil**; a strong updraft may punch above it as an **overshooting top**.

3. Dissipating stage: downdrafts spread through the whole cloud and cut off the warm, moist inflow. The storm rains itself out and only the anvil lingers.

A storm drifts with the winds of the middle troposphere, usually at 20–40 km/h; a well-organised supercell may race along at 65–80 km/h. Its path is irregular because each new cell grows where the outflow of the old one lifts fresh air.

DOWNBURSTS: A HAZARD FOR AIRCRAFT

A **downburst** is a strong downdraft that hits the ground and spreads out in all directions. A **macroburst** covers more than 4 km; a **microburst** is smaller but can produce winds of over 200 km/h for a few minutes. An aircraft flying through one meets a headwind, then a sudden tailwind and a downward push, a deadly sequence during take-off and landing. Airports now use Doppler radar and wind-shear alerts to spot them.

02 Types of Thunderstorms

Thunderstorms can be grouped by what lifts the air (convective, frontal, orographic) or, as meteorologists usually do, by how organised they are. Organisation depends mostly on **vertical wind shear**, the change of wind speed and direction with height. Weak shear gives short-lived single cells; strong shear tilts the updraft away from the rain so the storm can feed itself for hours.

Anatomy of a Supercell Thunderstorm

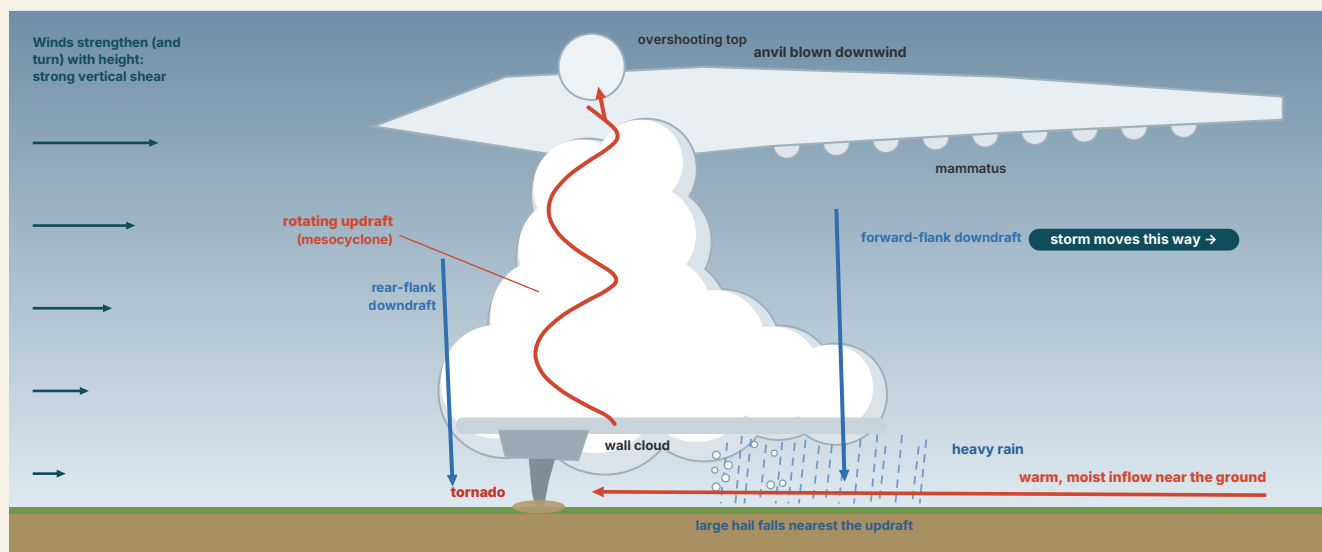


Fig. 20.3 In a supercell the updraft rotates and leans, so rain and hail fall to one side (the forward flank) and the updraft keeps drawing in warm, moist air. Tornadoes form under the rotating updraft, near the rear-flank downdraft.

TYPE	STRUCTURE	LIFE AND WEATHER	TYPICAL SETTING
Single-cell (air-mass) storm	One updraft–downdraft cell; forms in weak shear	Under an hour; brief downpour, some lightning, small hail	Summer afternoons in the tropics; the pre-monsoon showers of south India
Multicell cluster	A group of cells at different stages; new cells form on the gust front of old ones	Several hours; heavy rain, hail, gusty winds, flash floods	Very common across India in the pre-monsoon and monsoon

Squall line (multicell line)	A long line of cells along a cold front or gust front	Strong straight-line winds; a long-lived, fast line is a derecho	Kalbaisakhi lines of eastern India; US Midwest
Supercell	A single huge cell with a rotating updraft (mesocyclone); needs strong shear	One to several hours; giant hail, violent gusts, most strong tornadoes	Great Plains of the USA; occasionally Bangladesh and eastern India
Mesoscale convective system	Hundreds of km of merged storms under one cloud shield	Half a day or more; widespread heavy rain	Monsoon lows, the Sahel, the Amazon

The Supercell

A **supercell** is the most dangerous kind of thunderstorm. Winds that strengthen and turn with height make the rising air spin, and the whole updraft rotates as a **mesocyclone**, a vortex a few kilometres wide. Because the updraft is tilted, rain falls out away from it instead of choking it, so the storm can last for hours. On radar a supercell often shows a hook-shaped echo, and under the updraft a lowered, rotating **wall cloud** may form. Tornadoes drop from the wall cloud.



Fig. 20.4 A wall cloud under a supercell: the rotating base from which a tornado may descend.

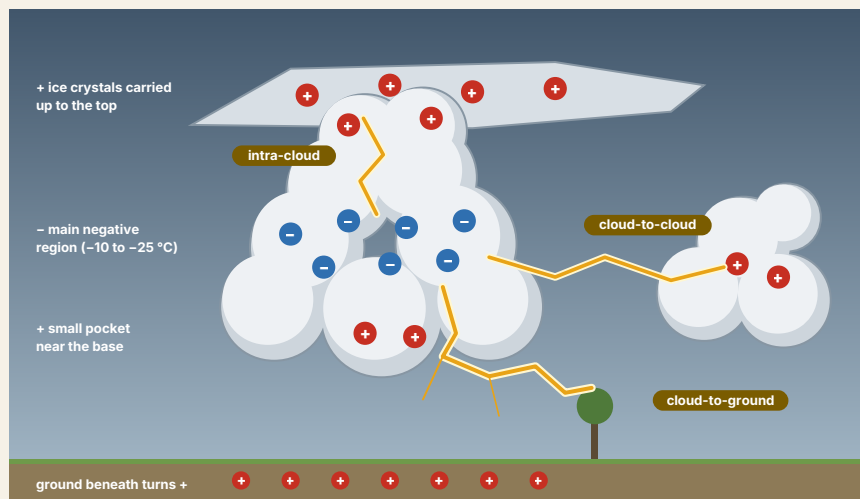
Fire-made storms: pyrocumulonimbus

Very large wildfires can build their own thunderstorm. The heat drives a smoke-laden plume high into the troposphere, where it cools and condenses into a **pyrocumulonimbus** cloud. Its lightning can start new fires far ahead of the front, and its inrushing winds fan the flames. Such clouds formed in the Australian bushfires of 2019–20 and the Canadian fires of 2023, and some injected smoke into the stratosphere.

03 Lightning and Thunder

Lightning is a giant electric spark that equalises charges built up inside a thunderstorm. Charge builds up in the **mixed-phase zone** of the cloud, where supercooled water, ice crystals and soft hail (**graupel**) exist together at about -10 to -20 °C. When graupel and crystals collide in the updraft, the heavier graupel tends to take **negative** charge and sink, while the light crystals take **positive** charge and are carried to the top. The cloud becomes a huge battery: **positive at the top, negative in the middle, with a small positive pocket near the base**. The ground beneath, normally neutral, becomes positive by induction.

How a Thunderstorm Charges Up, and Where Lightning Strikes



HOW THE CHARGE SEPARATES

mixed-phase zone (-10 to -20 °C)

graupel

ice crystals

Soft hail (graupel) and tiny ice crystals collide in the updraft. Graupel takes negative charge and sinks; light crystals take positive charge and are lifted to the top of the cloud.

Flash-to-bang: count the seconds from flash to thunder; $3 \text{ s} \approx 1 \text{ km}$

Fig. 20.5 Collisions between graupel and ice crystals separate charge. Most flashes stay inside the cloud; about a quarter strike the ground, preferring tall, isolated objects.

- **Types:** most flashes are **intra-cloud**; others jump **cloud to cloud**. Only about a quarter are **cloud-to-ground**, but these do the damage.
- **How a strike happens:** a faint, branching **stepped leader** of negative charge zigzags down from the cloud. When it nears the ground, a **streamer** of positive charge rises from a tree, tower or person to meet it, completing the channel. A brilliant **return stroke** then races upwards. The voltage can reach hundreds of millions of volts, the current around 30,000 amperes on average, and the channel heats to about **30,000 °C, roughly five times hotter than the Sun's surface**.
- **Thunder** is the sound of that air expanding explosively. The heated channel bursts outwards faster than sound, and the shock wave decays into the rumble we hear. Light arrives almost instantly but sound travels about 1 km in 3 seconds, so counting from flash to bang gives the distance of the strike. Thunder is **not** caused by clouds colliding, as UPSC tested in 2013.
- **Benefits:** lightning splits nitrogen molecules, and the nitrogen oxides formed reach the soil with rain as natural fertiliser. It also makes some ozone, and it starts many natural forest fires.

Records

- The world's lightning capital is **Lake Maracaibo** in Venezuela, where warm water, mountains on three sides and nightly breezes make the "**Catatumbo lightning**" storms that flash on about 300 nights a year.
- The longest single flash confirmed by the WMO (announced in 2025) stretched **829 km** across the US Great Plains in October 2017; the longest-lasting, over Uruguay and Argentina in 2020, glowed for about 17 seconds.



Fig. 20.6 Cloud-to-ground strokes over the sea. Each visible bolt is a channel only a few centimetres wide.

Lightning in India

Lightning is now **India's biggest killer among natural hazards**. National Crime Records Bureau data show 2,887 deaths from lightning in 2022, over a third of all deaths from natural causes that year, and roughly 2,000–3,000 a year through the last decade. Most victims are farmers, labourers and herders caught in open fields during the pre-monsoon and early monsoon months.

- **Hotspots:** Bihar, Jharkhand, Odisha, West Bengal, Madhya Pradesh and Uttar Pradesh. The Chhota Nagpur plateau, where moist air from the Bay of Bengal meets hot, dry air over high ground, is among the most lightning-prone areas in Asia.

- **Why people die:** a direct hit is rare but usually fatal. More people are killed by **ground current** spreading from a struck tree or pole, or by "side flash" while sheltering under a tree. Wet ground and metal make it worse.
- **Warnings:** IMD and the Indian Institute of Tropical Meteorology (IITM), Pune run a lightning location network and nowcasts; the **Damini** app warns users of strikes within about 20–40 km. Odisha has planted palm trees, which act as natural lightning conductors, and the Lightning Resilient India Campaign has pushed for local action plans.
- **Safety:** if thunder follows the flash within 30 seconds, take shelter, and wait 30 minutes after the last thunder. In the open, crouch low with feet together; never lie flat or stand under a lone tree.

IN THE NEWS · LIGHTNING AND HEATWAVES NOTIFIED AS DISASTERS (2026)

For years lightning was not on the Centre's list of notified disasters, which decides what the **State and National Disaster Response Funds (SDRF/NDRF)** pay for. States could only call it a "state-specific disaster" and spend up to 10% of their SDRF on it, as **Odisha did from 1 April 2015** and Kerala also did. The **Sixteenth Finance Commission** (report submitted November 2025) recommended adding lightning and heatwaves, and in **August 2026** the Union Government told Parliament that both have been notified. The list now covers 14 hazards: cyclone, drought, earthquake, fire, flood, tsunami, hailstorm, landslide, avalanche, cloudburst, pest attack, frost and cold wave, plus **heatwave and lightning**.

04 Hail, Cloudbursts and India's Local Storms

Hail

Hail is precipitation in the form of balls or lumps of ice, 5 mm or more across, that fall from a cumulonimbus. Small hail forms in most thunderstorms but melts on the way down; a storm that drops hail on the ground is a **hailstorm**.

How a Hailstone Grows

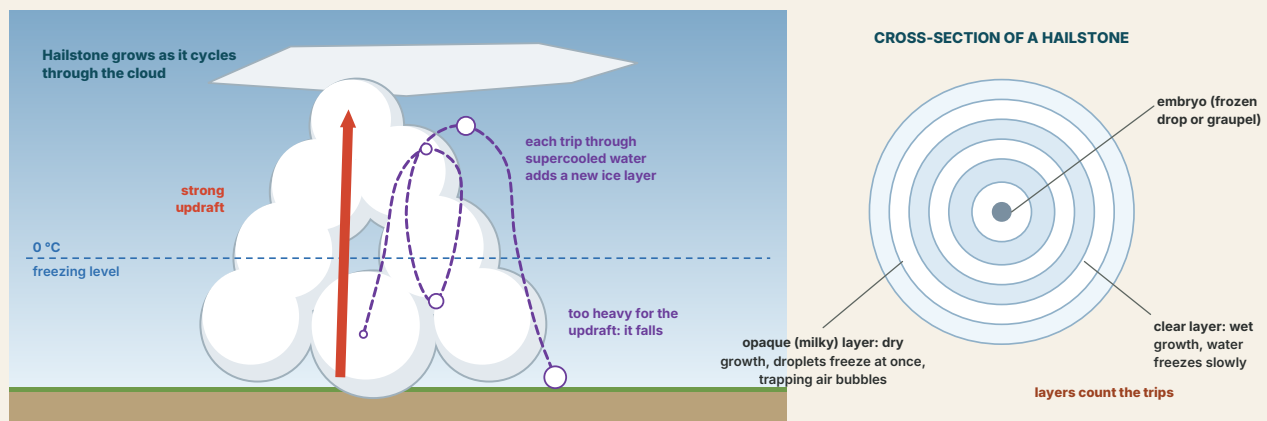


Fig. 20.7 A strong updraft keeps a growing hailstone aloft in the zone of supercooled water. Each pass adds a clear or milky layer, and the stone falls only when it is too heavy for the updraft to hold.

- **Growth:** a frozen drop or graupel pellet (the embryo) is carried up through cloud droplets cooled below 0 °C but still liquid (**supercooled**). They freeze onto it. Where water is plentiful it spreads before freezing and forms a **clear** layer; where it freezes at once it traps air and forms an **opaque**, milky layer. Cutting a hailstone reveals these rings.
- **Conditions for big hail:** a strong, long-lived updraft (supercells are best), plenty of supercooled water, a tall cloud with much of it below freezing, and a freezing level low enough that stones do not melt before landing.
- Hail is **less common in the tropics** than in the mid-latitudes even though thunderstorms are more frequent there, because the freezing level is high and stones melt in the deep warm layer.
- **Records:** the largest hailstone measured, at Vivian, South Dakota (2010), was 20 cm across; the heaviest, about 1 kg, fell at Gopalganj in Bangladesh in 1986.

In India hail strikes mainly from February to April, when western disturbances bring cold air aloft over moist air from the south. Maharashtra (Vidarbha and Marathwada), Madhya Pradesh, Telangana, Rajasthan and Punjab regularly lose rabi wheat, gram, fruit and vegetable crops. Hailstorm is a notified disaster.

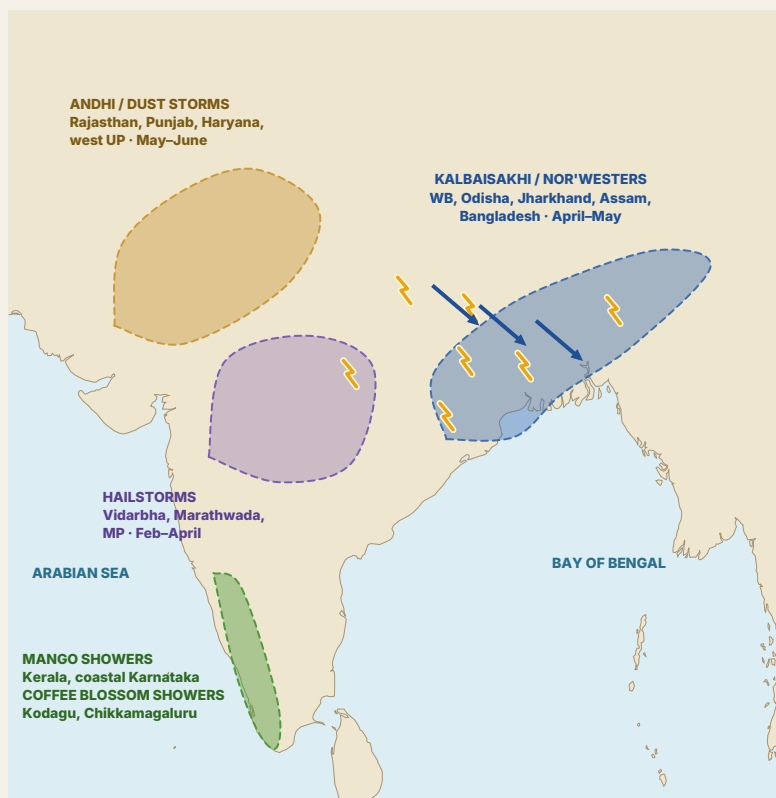


Fig. 20.8 Hailstones after a storm.

India's Pre-Monsoon Storms

- **Kalbaisakhi (Nor'westers):** "the calamity of Baisakh". Violent evening thunderstorms of April and May in West Bengal, Odisha, Jharkhand, Bihar, Assam and Bangladesh. They usually approach from the north-west as a dark arch of cloud, with squalls that can top 100 km/h, hail and sometimes tornadoes. Warm, humid air from the Bay of Bengal lies under hot, dry air from the plateau and plains; when it is lifted, the unstable layer erupts. In Assam they are called **Bordoisila**. The rain helps tea, jute and aus rice.
- **Mango showers:** pre-monsoon thundershowers of April–May along the Kerala and coastal Karnataka coast, which help mangoes ripen. **Blossom (coffee) showers** in Kodagu and Chikkamagaluru make coffee plants flower.
- **Andhi** and dust storms over Rajasthan, Punjab, Haryana and western Uttar Pradesh; the **loo**, by contrast, is a hot, dry wind, not a storm.

Severe Local Storms of India



PRE-MONSOON STORMS (MARCH–MAY)

- **Kalbaisakhi (Nor'westers)**
Violent evening squalls that arrive from the north-west. Moist air from the Bay of Bengal lies under hot, dry air; once lifted, it erupts. Called Bordoisila in Assam. Rain helps tea, jute and aus rice.
- **Andhi and dust storms**
Hot, dry squalls raise walls of dust over the north-western plains. On 2 May 2018 dust storms killed more than 120 people in Rajasthan and Uttar Pradesh.
- **Mango and blossom showers**
Pre-monsoon thundershowers in Kerala and Karnataka; they help mangoes ripen and coffee plants flower.
- **Hailstorms**
Western disturbances meeting moist air from the south batter rabi crops.
- **Lightning hotspots**
Chhota Nagpur plateau and the eastern plains: Bihar, Jharkhand, Odisha, West Bengal, MP and UP record the most deaths.

Land outline only; zones are approximate.

Fig. 20.9 Between March and May, heating of the land meets moisture from the seas and gives India a season of violent local storms, each with its own region and name.

Cloudbursts

A **cloudburst**, in IMD's working definition, is rainfall of 100 mm (10 cm) or more in an hour over a small area of about 20–30 square kilometres. It is a thunderstorm's rain released almost all at once, not literally a cloud bursting.

- **Mechanism:** moisture-laden monsoon air is forced up steep mountain slopes. The rising air builds a tall cumulonimbus that stays locked over one valley, held in place by the terrain or by weak steering winds. Strong updrafts hold up a huge load of drops; when they weaken, the whole load falls in minutes. An interaction between the monsoon and a western disturbance can make the lift stronger.
- **Where:** mostly in the Himalaya (Uttarakhand, Himachal Pradesh, Jammu and Kashmir, Ladakh) and the Western Ghats, during the monsoon.
- **Effects:** flash floods, debris flows and landslides in narrow valleys, often at night and with little warning. Examples include **Leh (August 2010)**, the **Kedarnath disaster (June 2013)**, many events in Himachal Pradesh in 2023 and 2025, and the cloudburst at **Chasoti in Kishtwar (August 2025)** on the Machail Mata pilgrimage route.
- Single radar or rain-gauge stations rarely catch them, so many events are confirmed only afterwards. Dense automatic weather stations and Doppler radars in the hills are the main answer.

Dust Storms



Fig. 20.10 A haboob rolls into Big Spring, Texas: dust lifted by a thunderstorm's outflow.

When a thunderstorm's cold downdraft hits dry, loose ground, its gust front lifts a wall of dust that can be a kilometre high. This is a **haboob** (from Sudan; also common in Arizona and the Arabian Peninsula). In north-western India such hot, dusty squalls of May and June are called **andhi**. On **2 May 2018** dust storms and thunderstorms killed more than 120 people in Rajasthan and Uttar Pradesh. Dust storms also carry nutrients across oceans: Saharan dust fertilises the Amazon.

05

Tornadoes and Waterspouts

A **tornado** (or "twister") is a violently rotating column of air that hangs from a thunderstorm cloud and touches the ground. It is the smallest but most intense of all storms: usually 50 m to a kilometre or so wide, lasting minutes and travelling a few kilometres. Doppler radar measured winds of about 480 km/h in the Oklahoma tornado of 3 May 1999, the fastest winds ever recorded near the Earth's surface. Pressure inside the funnel can drop sharply, and the visible funnel is cloud formed by that pressure fall, darkened by dust and debris.

How a Tornado Forms

1. Where warm, moist air lies under a strong wind aloft, the change of wind with height (**vertical wind shear**) sets the lower air rolling about a horizontal axis.
2. A thunderstorm's updraft lifts this roll and tilts it upright, so the updraft itself begins to rotate: the **mesocyclone** of a supercell.
3. Downdrafts on the storm's rear flank wrap around the rotation and help bring it to the ground. As the spinning column is stretched and narrowed, it spins faster, as a skater does when she pulls in her arms (conservation of angular momentum). When it touches the ground it is a tornado.

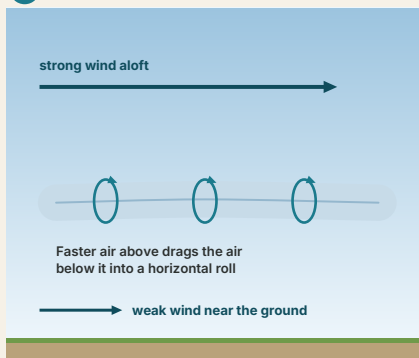


Fig. 20.11 A tornado near Anadarko, Oklahoma, on 3 May 1999, during the outbreak that produced the record winds.

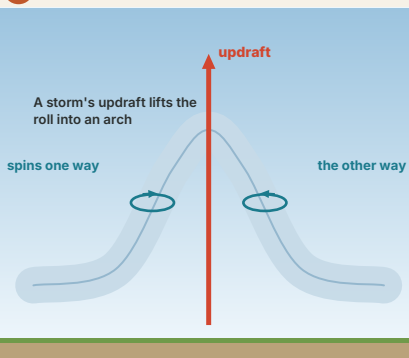
In the northern hemisphere most tornadoes turn anticlockwise, as their parent mesocyclones do, though a few turn the other way. Coriolis force is far too weak at this small scale to decide the spin directly.

From Wind Shear to Tornado

1 SHEAR SETS THE AIR ROLLING



2 UPDRAFT TILTS THE ROLL UPRIGHT



3 MESOCYCLONE STRETCHES INTO A TORNADO

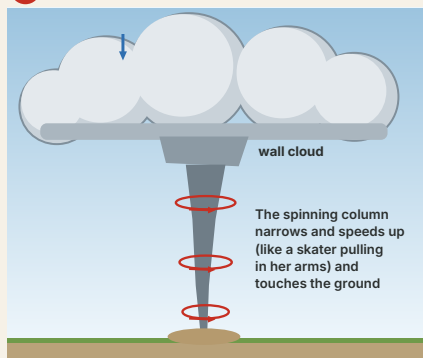


Fig. 20.12 Shear creates a horizontal roll of spinning air; a storm's updraft tilts it upright into a mesocyclone; the narrowing column spins faster and reaches the ground.

Rating Tornadoes: The Enhanced Fujita Scale

Tornado winds are rarely measured directly, so they are rated from the **damage** they do. The **Enhanced Fujita (EF) scale**, used in the USA since 2007, replaced the original Fujita scale of 1971.

RATING	ESTIMATED 3-SECOND GUST	TYPICAL DAMAGE
EF0	105–137 km/h	Broken branches, damaged roofs and gutters
EF1	138–177 km/h	Roofs stripped, mobile homes overturned
EF2	178–217 km/h	Roofs torn off houses, large trees snapped
EF3	218–266 km/h	Whole storeys of well-built houses destroyed
EF4	267–322 km/h	Well-built houses levelled, cars thrown
EF5	over 322 km/h	Strong frame houses swept away; steel-reinforced buildings badly damaged

Where Tornadoes Strike: Tornado Alley

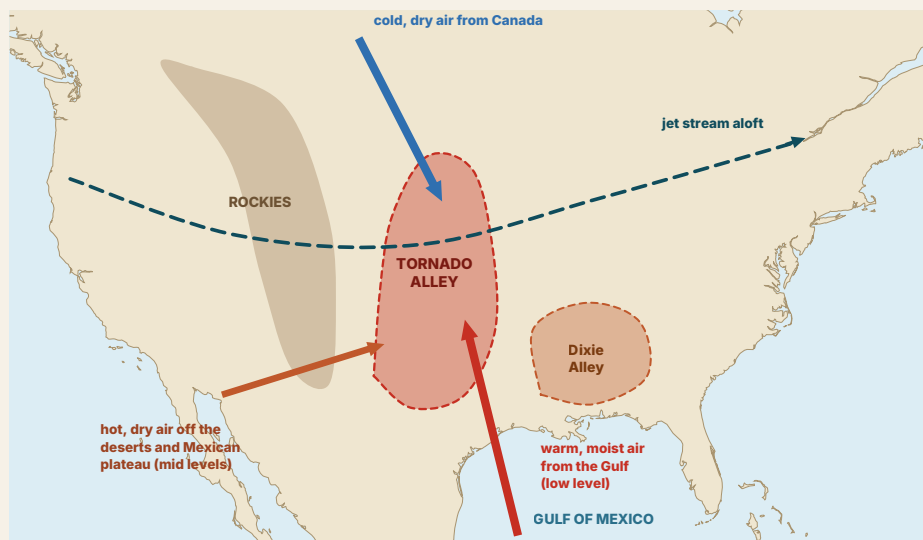
Tornadoes have been seen on every continent except Antarctica, mostly in the mid-latitudes in spring and early summer. The **United States has by far the most, about 1,200 a year**, and Canada the second most. Per unit area, the Netherlands and the United Kingdom report many small ones. The deadliest tornadoes have struck **Bangladesh**, where crowded, flimsy housing meets pre-monsoon supercells: the **Daulatpur–Saturia tornado of April 1989** killed about 1,300 people.

This answers the Mains 2024 question on why most twisters occur around the Gulf of Mexico. The Gulf supplies the warm, moist fuel; the Rockies and Mexican plateau supply a "lid" of dry air that lets heat build up under it until storms break through explosively; fronts and the dry line supply lift; and the jet stream above southerly surface winds supplies the shear that makes storms rotate. No mountain range runs east–west to keep the air masses apart. **Tornado Alley** runs from Texas through Oklahoma and Kansas to Nebraska and South Dakota; **Dixie Alley** in the south-eastern states has fewer tornadoes but more deaths, because its storms are often hidden by rain, strike at night and hit wooded, more crowded country.

Tornadoes in India

Tornadoes are uncommon in India and usually weak, occurring with nor'westers over West Bengal, Odisha, Bihar, Assam and the north-east, and occasionally in Punjab and Haryana. The deadliest on record struck Belda in Medinipur, West Bengal, on **24 March 1998**, killing about 250 people. A tornado that struck **Jalpaiguri** on 31 March 2024 killed five people and injured over a hundred.

Why the Great Plains Breed So Many Tornadoes



WHY THE GREAT PLAINS?

Moisture:
the warm Gulf feeds humid air north with no mountain barrier

Lid and instability:
dry desert air above traps heat and moisture until storms burst through violently

Lift:
cold fronts from Canada and the dry line force the air up

Shear:
southerly winds below, strong westerly jet above: storms rotate

Flat land:
nothing breaks up the air streams

USA: about 1,200 tornadoes a year, peak April to June

Fig. 20.13 In spring three air streams meet over the flat interior of North America: humid air from the Gulf of Mexico at the surface, hot, dry air from the south-west above it, and cold air from Canada behind fronts, all under a strong jet stream. Zones are approximate.

Waterspouts



Fig. 20.14 A waterspout off Mallorca, Spain.

A **waterspout** is a rotating column of air over water, joined to a cumuliform cloud. **Tornadic waterspouts** are true tornadoes that form over water or move onto it, and are as dangerous. The more common **fair-weather waterspouts** grow upwards from the water surface under developing cumulus clouds, without a supercell; they are weaker and short-lived. Despite appearances, a waterspout does not suck up a column of sea water; the visible funnel is mostly condensed cloud, with spray at its base. They are frequent over warm, shallow seas such as the Florida Keys and the Mediterranean.

FEATURE	TORNADO	TROPICAL CYCLONE
Size	Tens of metres to about 2 km	Hundreds of km (often 500–1,000 km)
Life	Minutes to an hour	Days to two weeks
Where it forms	Over land, under a thunderstorm; mostly mid-latitudes	Over warm tropical oceans; weakens over land
Energy source	The parent storm's rotating updraft	Latent heat from evaporation off a warm sea
Strongest winds	Up to about 480 km/h	Up to about 300 km/h
Main killer	Wind and flying debris	Storm surge and floods, then wind
Relation	Tornadoes often spin off in the outer rain bands of a cyclone after landfall	

06

Cyclones and Anticyclones: The Basics

In everyday Indian usage "cyclone" means a tropical storm, but in meteorology a **cyclone** is any area of **low pressure** around which air circulates, and an **anticyclone** is any area of **high pressure**. Because of the Coriolis effect and friction, air spirals in towards a low and out of a high, in opposite senses in the two hemispheres.

FEATURE	CYCLONE (LOW)	ANTICYCLONE (HIGH)
Pressure at centre	Lowest; isobars close together, steep gradient	Highest; isobars widely spaced, gentle gradient
Surface winds (northern hemisphere)	Converge, spiralling inwards anticlockwise	Diverge, spiralling outwards clockwise
Surface winds (southern hemisphere)	Converge clockwise	Diverge anticlockwise
Vertical motion	Rising air, which cools and condenses	Sinking air, which warms and dries
Weather	Clouds, rain, strong winds, storms	Clear skies, light winds, stable air; heatwaves in summer, fog, frost and smog in winter
Kinds	Tropical cyclones; temperate (extratropical) cyclones; heat lows; polar lows	Subtropical highs; polar highs; cold continental highs (Siberian High); blocking highs

A slow-moving **blocking high** can park over a region for weeks, steering storms around it and baking the land beneath it, as in the heatwaves of Europe and north-west India. The mid-latitude highs and lows that travel with the westerlies, and the fronts between air masses, are the subject of Chapter 21. The rest of this chapter deals with the tropical storm.

BASIS	TROPICAL CYCLONE	TEMPERATE CYCLONE (CHAPTER 21)
Origin and energy	Thermal: forms within one warm, moist air mass; latent heat	Dynamic: forms on a front between warm and cold air masses; temperature contrast
Fronts	None	Warm and cold fronts
Where	Over warm seas (about 5°–25°); dies over land	Over land and sea (about 35°–65°)
Size, winds	Smaller, but winds far stronger	Larger (up to 2,000 km), gentler winds
Movement	East to west, then recurving	West to east with the westerlies
Life	About a week	One to three weeks

07

Tropical Cyclones: Conditions for Formation

A **tropical cyclone** is an intense, warm-cored low-pressure system that forms over a tropical ocean, with a closed, rapidly rotating circulation, a ring of towering thunderstorms around its centre, spiral bands of rain and winds of at least 62 km/h. Its strongest forms are the **hurricane, typhoon and very severe cyclonic storm** (winds of 119 km/h or more). Unlike a thunderstorm it is a long-lived, self-sustaining system: the ocean is its fuel tank.

A Heat Engine

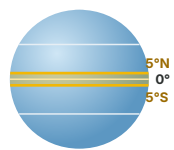
A tropical cyclone works like a **heat engine**. Strong winds evaporate huge quantities of water from the warm sea. As the moist air spirals in and rises in the eyewall, the vapour condenses and releases **latent heat of condensation**. This warms the core, lowers the surface pressure further, draws in more air faster, and evaporates still more water. The chain runs as long as warm water lies beneath. A mature hurricane releases heat at a rate estimated at about 200 times the world's total electricity-generating capacity, though only a small fraction of it goes into wind.

Six Conditions That Breed a Tropical Cyclone

1 WARM, DEEP OCEAN

Sea surface at least $\geq 26.5^{\circ}\text{C}$, and warm water about 50–60 m deep, so the storm's own churning does not bring up cold water. Fuel: evaporation and latent heat.

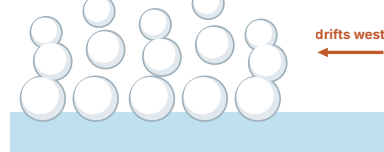
2 ENOUGH CORIOLIS FORCE



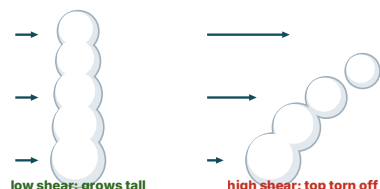
Coriolis force is zero at the equator. Storms rarely form within about 5° of it; it gives the inflowing air its spin (anticlockwise in the north, clockwise in the south).

3 A PRE-EXISTING DISTURBANCE

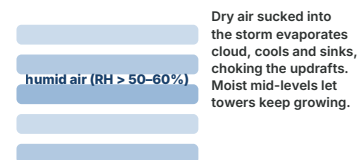
A cluster of thunderstorms, an easterly wave or a monsoon low gives the seed



4 LOW VERTICAL WIND SHEAR



5 MOIST MIDDLE TROPOSPHERE



6 DIVERGENCE ALOFT

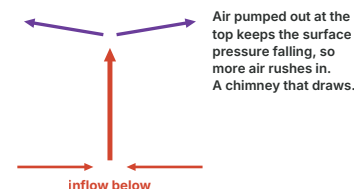


Fig. 20.15 All six must come together, which is why only a small fraction of tropical disturbances ever become cyclones.

- 1. A warm, deep ocean:** sea-surface temperature of at least $26.5\text{--}27^{\circ}\text{C}$, with the warm layer reaching about **50–60 m**. A shallow warm skin is not enough: the storm's own winds churn the sea, and if cold water lies close below, they bring it up and starve the storm.
- 2. Enough Coriolis force:** the deflection that makes inflowing air spin is zero at the equator and grows with latitude. Cyclones seldom form within about 5° of the equator; about two-thirds form between 10° and 20° .
- 3. A pre-existing disturbance:** a cluster of thunderstorms with slightly low pressure, such as an **easterly wave** drifting west in the trade winds, a monsoon trough or low, or the remains of an older storm. Cyclones do not form out of a calm sea.
- 4. Low vertical wind shear:** winds that change little in speed and direction between the lower and upper troposphere. Strong shear tilts the storm and blows the heat and moisture away from its core. This is why cyclones are confined to the tropics, equatorward of the subtropical jet, and why few form during the south-west monsoon.
- 5. A moist middle troposphere:** relative humidity of 50–60% or more at 3–6 km. Dry air drawn into the storm evaporates cloud, cools and sinks, weakening the updrafts.
- 6. Upper-level divergence:** an outflow aloft that removes the rising air, like a chimney with a good draught. Without it, air piles up over the storm and surface pressure stops falling.

Four Questions UPSC Likes

Why do no cyclones form at the equator?

With no Coriolis force, inflowing air simply fills the low instead of spinning around it. Exceptions within 5° are rare:

Typhoon Vamei (December 2001) formed at about 1.5°N near Singapore, and **Cyclone Senyar** (November 2025), the first recorded cyclone in the Strait of Malacca, formed a few degrees north of the equator and brought catastrophic floods to Sumatra, with more than a thousand deaths.

Why none in the South Atlantic and south-east Pacific? (Prelims 2015)

Their **sea-surface temperatures are too low**. The cold Benguela and Humboldt (Peru) currents and upwelling chill the eastern parts of these oceans; the South Atlantic also has strong wind shear and the ITCZ seldom moves south over it, so there are few seedling disturbances. The same logic explains why cyclones form mostly on the **western sides of the tropical oceans**: the trade winds drive warm water westwards and pile up a thick warm layer there, while cold currents flank the western



coasts of the continents. Only in strong El Niño years does the eastern Pacific become warm enough for unusual storms.

Fig. 20.16 Cyclone Catarina, March 2004, seen from the ISS: the first hurricane-strength storm recorded in the South Atlantic. It struck southern Brazil.

Why more in the northern hemisphere? (Mains 2014)

- The **thermal equator** (ITCZ) lies north of the geographical equator for most of the year, so the warmest water and the seedling disturbances sit there.
- The northern hemisphere's oceans are smaller and hemmed in by land, so they warm more in summer; the vast, cold Southern Ocean and Antarctica keep southern waters cooler and winds stronger (higher shear).
- Basins such as the **South China Sea, Bay of Bengal and Gulf of Mexico** are warm, partly enclosed seas fed by monsoon or easterly-wave disturbances and by large rivers whose fresh water forms a stable warm surface layer.

Why late summer and autumn?

Water heats slowly, so the sea reaches its warmest in August–October in the northern hemisphere, a month or two after the land. The ITCZ is then farthest from the equator, where the Coriolis force is stronger. In the North Indian Ocean the monsoon complicates the pattern (Section 12).

08 Where Tropical Cyclones Form

Around 80–90 tropical storms reach named strength each year worldwide, about two-thirds of them in the northern hemisphere. The **north-west Pacific is the busiest basin**, with about a third of the world's total; the North Indian Ocean has only about 5–6% of storms but, because of its crowded low-lying coasts, a large share of the deaths.

Tropical Cyclone Basins, Regional Names and Typical Tracks

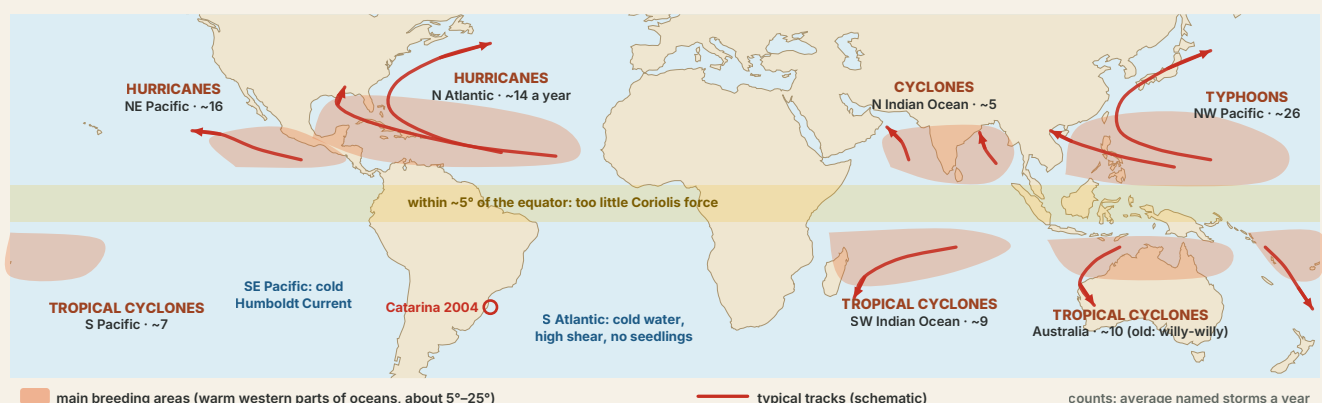


Fig. 20.17 Storms form over the warm western parts of the tropical oceans, move west with the trade winds and then recurve poleward. The South Atlantic and south-east Pacific, chilled by cold currents, are almost free of them.

REGION	REGIONAL NAME	MAIN SEASON	WARNING CENTRE
North Atlantic, Caribbean, Gulf of Mexico; central and eastern North Pacific	Hurricane	June–November (peak September)	National Hurricane Center, Miami; Honolulu
North-west Pacific, South China Sea (Philippines, China, Japan, Vietnam)	Typhoon (in the Philippines also "bagyo")	All year; peak July–October	Japan Meteorological Agency, Tokyo
North Indian Ocean (Bay of Bengal, Arabian Sea)	Cyclone, cyclonic storm	April–June and October–December	IMD, New Delhi
South-west Indian Ocean (Madagascar, Mozambique, Mauritius)	Tropical cyclone	November–April	Météo-France, La Réunion

Australia and south-west Pacific

Tropical cyclone (historically "willy-willy" off north-west Australia)

November–April

Australian Bureau of Meteorology; Fiji (Nadi)

The WMO recognises six **Regional Specialised Meteorological Centres (RSMCs)** for tropical cyclones, of which IMD New Delhi is one, plus several Tropical Cyclone Warning Centres. Each region names and tracks its own storms.

Unusual relatives

- **Medicanes** ("Mediterranean hurricanes") form over the Mediterranean in autumn and winter. They have an eye and a warm core but are smaller and weaker. **Storm Daniel** (September 2023) caused the dam failures at Derna in Libya that killed thousands.
- **Hybrid** or subtropical storms share features of tropical and temperate cyclones; tropical cyclones moving into cold water often become extratropical storms (Chapter 21).
- **Twin cyclones** form at the same time on either side of the equator, at similar longitudes, spinning in opposite senses. They are usually triggered by an active pulse of the **Madden–Julian Oscillation (MJO)**, an eastward-moving band of enhanced convection that circles the tropics every 30–60 days. In May 2022 **Asani** (Bay of Bengal) and **Karim** (South Indian Ocean) formed as twins.

09 Life Cycle and Structure of a Cyclone

From Disturbance to Cyclone

1. **Tropical disturbance:** an area of organised thunderstorms persisting for a day or more, with a slight fall in pressure. Most never develop further.
2. **Depression:** the pressure falls, air begins to circulate around a closed centre and the Coriolis force sets it spinning. IMD calls a system a depression when sustained winds reach 31 km/h, and a deep depression at 50 km/h.
3. **Cyclonic storm (tropical storm):** winds reach **62 km/h** (34 knots); the system takes on its spiral shape and is given a name.
4. **Severe stages:** at **119 km/h** (64 knots) and above it is a hurricane, typhoon or very severe cyclonic storm, and usually develops a clear **eye**.
5. **Decay:** the storm weakens when it crosses land and loses its supply of moisture (and gains friction), moves over cooler water, or meets strong shear. Many recurve into the mid-latitudes and turn into extratropical storms.

Why does an eye form? As air spirals inwards it spins faster, and close to the centre the outward (centrifugal) pull of the spin balances the inward pressure force, so the air can get no closer. It turns upwards in a ring, the eyewall. Some of the air that has risen in the eyewall sinks gently into the middle, warming as it is compressed, which clears the cloud and creates the eye.

Anatomy of a Mature Cyclone

- **Eye:** the calm, often cloud-free centre, usually **20–60 km** across (from under 10 km to over 200 km). It has the **lowest surface pressure** and light winds. Its air sinks slowly and is warmed by compression, so the eye is **warmer than its surroundings**, by as much as **10 °C or more at 10–12 km**, though only slightly at the surface. Stars or blue sky may be seen through it. Intense, compact storms often have the smallest, clearest eyes ("pinhole eyes"); not every cyclone develops an eye.
- **Eyewall:** the ring of tall cumulonimbus around the eye, sloping outwards with height like the seats of a stadium. It has the **strongest winds and heaviest rain**. In strong storms a new outer eyewall can form and replace the inner one (an **eyewall replacement cycle**), briefly weakening the storm and widening its wind field.

Cross-Section of a Mature Tropical Cyclone

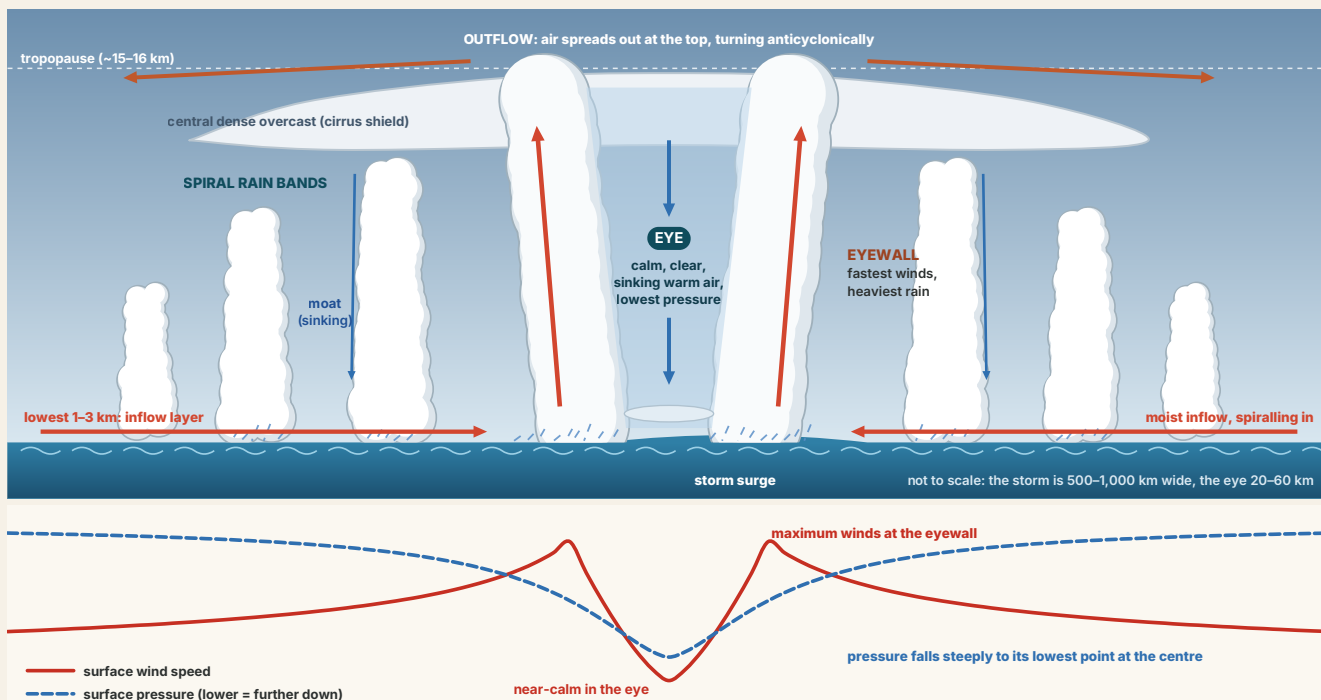


Fig. 20.18 Air spirals in at the surface, rises in the eyewall and rain bands, and spreads out at the top. Below: wind speed peaks at the eyewall and drops to near calm in the eye, where pressure is lowest.

- **Spiral rain bands:** long curved bands of thunderstorms that spiral in towards the centre, with clearer zones of sinking air between them. Inner bands are mostly cumulonimbus; outer ones contain nimbostratus and cumulus.
- **Central dense overcast (CDO):** the shield of cirrus, made of ice crystals, that spreads from the eyewall and inner bands at the top of the storm and hides them on satellite images until the eye clears.
- **Vertical layers:** the **inflow layer** in the lowest 1–3 km, where air converges and drives the storm; the **middle layer** of rising air; and the **outflow layer** near the tropopause (about 12–15 km), where air spreads out and turns clockwise (anticyclonic) in the northern hemisphere.
- **Size:** the cloud system is usually 500–1,000 km across; the belt of damaging winds is much narrower. Isobars are nearly circular and very closely spaced.

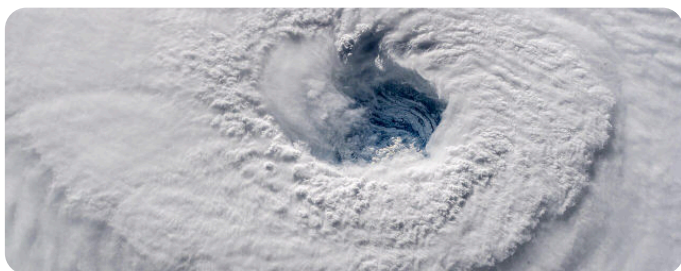


Fig. 20.19 Looking down into the eye of Hurricane Florence (2018) from the International Space Station: the eyewall clouds slope outwards like a stadium.

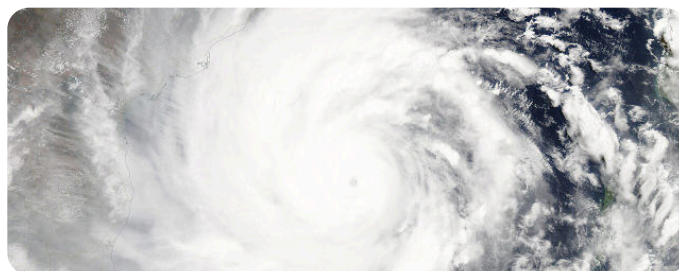


Fig. 20.20 Super Cyclone Amphan over the Bay of Bengal on 19 May 2020, a day before landfall in West Bengal. Note the spiral bands and the cirrus shield.

CLEARING A COMMON MISCONCEPTION

The eye is **not cold**. In 2020 UPSC offered the statement that the temperature inside the eye is nearly 10 °C lower than the surroundings; it is false, because sinking air warms the eye. The other correct statement in that question was that only some cyclones develop an eye.

Movement, Landfall and Hazards

How Cyclones Move

A cyclone is carried along by the large-scale winds around it, like a leaf in a stream; this is **steering**. In the northern hemisphere a typical storm forms on the southern side of a **subtropical high**, so the trade winds carry it **west** or west-north-west at 10–25 km/h. As it rounds the western edge of the high it turns **north**, usually near 20–25°N, and then the **westerlies** sweep it north-east, often faster. This parabolic path is called **recurvature**. Storms also drift slightly poleward on their own (the "beta drift"), because the Coriolis force is stronger on their poleward side.

- **Strongest on the right:** in the northern hemisphere the winds on the right-hand side of the track (relative to the direction of motion) blow in the same direction as the storm moves, so the two add up; on the left they partly cancel. The **right-front quadrant** also drives the highest storm surge. In the southern hemisphere it is the left side.
- **Fujiwhara effect:** when two cyclones come within roughly 1,400 km of each other, they begin to rotate around a common centre (anticlockwise in the northern hemisphere). The larger may absorb the smaller, they may merge, or one may fling the other away. Their tracks become erratic and hard to forecast; the interaction can also feed shear and dry air into one storm and weaken it. The effect was described by the Japanese meteorologist **Sakuhei Fujiwhara** in 1921, and it was asked in Mains 2026. Typhoons in the crowded north-west Pacific show it most often.
- **Stalling:** when the steering currents are weak, a storm can crawl or stall and dump enormous rain in one place, as Hurricane Harvey did over Houston in 2017 (over 1,500 mm). Studies suggest the average forward speed of tropical cyclones has slowed in recent decades.

Recurvature, the Dangerous Right Side and the Fujiwhara Effect

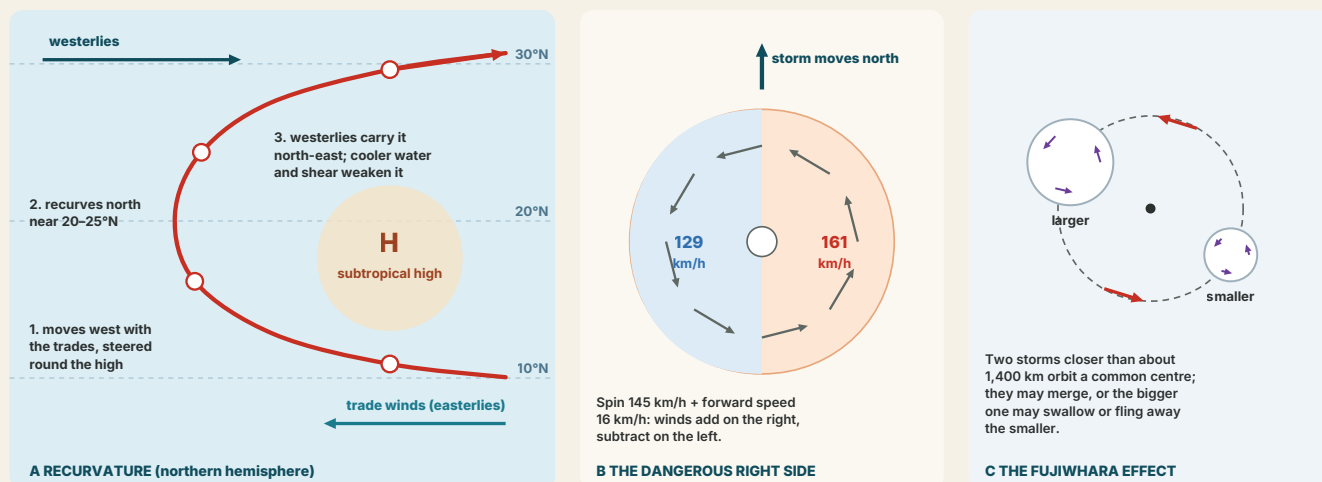


Fig. 20.21 A: steering by the subtropical high, trades and westerlies. B: in the northern hemisphere the forward motion adds to the wind on the right of the track. C: two nearby storms circle a common centre.

Rapid Intensification

Rapid intensification is an increase in maximum sustained winds of at least **55 km/h (30 knots) in 24 hours**. It happens over very warm, deep water with low shear and moist air, and it is dangerous because a storm can jump from minor to major just before landfall, leaving too little time to evacuate. Ockhi (2017), Tauktae (2021), Hurricane Milton (2024), which went from a tropical storm to Category 5 in about a day and a half, and Hurricane Melissa (2025) all intensified rapidly. Warming oceans are making it more frequent.

What Makes a Cyclone Deadly

- **Wind:** winds of 150–250 km/h uproot trees, flatten kutcha houses and power lines and turn debris into missiles. The force of wind rises with the square of its speed.

- **Rain and floods:** falls of 30–50 cm a day are common near the centre, causing river and urban flooding and landslides far inland. A slow, weaker storm can do more flood damage than a fast, strong one.
- **Storm surge:** an abnormal rise of the sea above the predicted tide as a cyclone comes ashore. It is **the biggest killer in most cyclone disasters**. Two effects combine: the **onshore winds pile water against the coast**, and the **low pressure lets the sea bulge up** (about 1 cm for each hPa of pressure drop). The surge is highest where the shelf is shallow and gently sloping and the coast is funnel-shaped, as at the **head of the Bay of Bengal**.
- **Storm tide:** the total water level, surge plus the astronomical tide. A surge that arrives at high tide, especially a spring tide, is far worse. Waves ride on top. Sea water poisons fields with salt for years and contaminates wells.

Storm Surge and Storm Tide

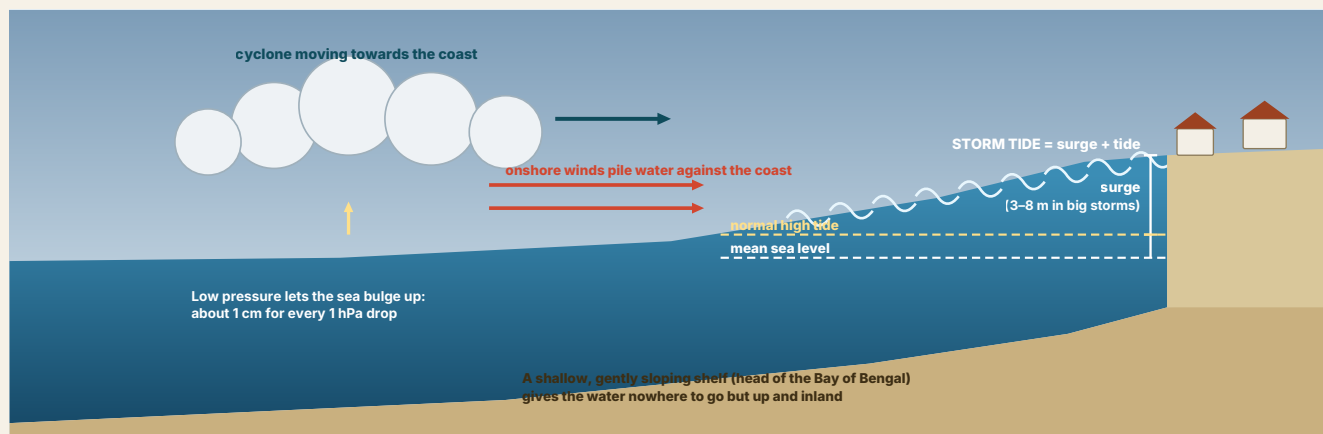


Fig. 20.22 Winds push water shoreward and low pressure lifts the sea; over a shallow shelf the water can only rise and flood inland. The surges of the 1970 Bhola cyclone and of Nargis (2008) were each several metres high.

The deadliest cyclones in history have all been surge disasters on deltas: the **Bhola cyclone of 1970** in what was then East Pakistan (roughly 3–5 lakh deaths), the Bangladesh cyclone of 1991, the **1999 Odisha super cyclone** and **Nargis (2008)**, which killed about 1.4 lakh people in Myanmar's Irrawaddy delta. Mangroves and shelterbelts break the surge: in 1999 villages behind the Bhitarkanika mangroves suffered far fewer deaths than exposed ones.

Not all bad

Cyclones move heat from the tropics towards the poles and help keep the planet's heat in balance; they bring vital rain to dry areas such as the rain-shadow interior of south India, Rayalaseema and Oman; they stir the ocean, breaking up harmful algal blooms (red tides) and cooling over-heated coral reefs; they move sand that rebuilds barrier islands; and they carry seeds and spores far inland.

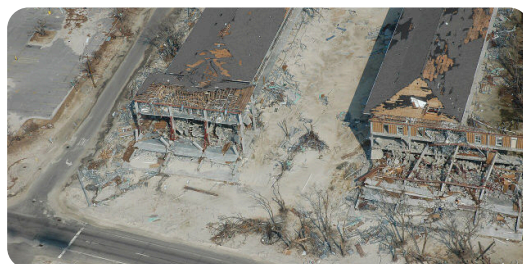


Fig. 20.23 Storm-surge damage on the Mississippi coast after Hurricane Katrina (2005).

11 Measuring and Naming Cyclones

Intensity Scales

Intensity is graded by the **maximum sustained surface wind**. The averaging period differs: the USA uses a 1-minute mean, India a **3-minute** mean and most other centres the WMO standard of 10 minutes, so the same storm can carry slightly different numbers. Speeds are usually measured in **knots** (1 knot = 1 nautical mile per hour = 1.852 km/h).

IMD Categories and the Saffir–Simpson Scale on One Axis

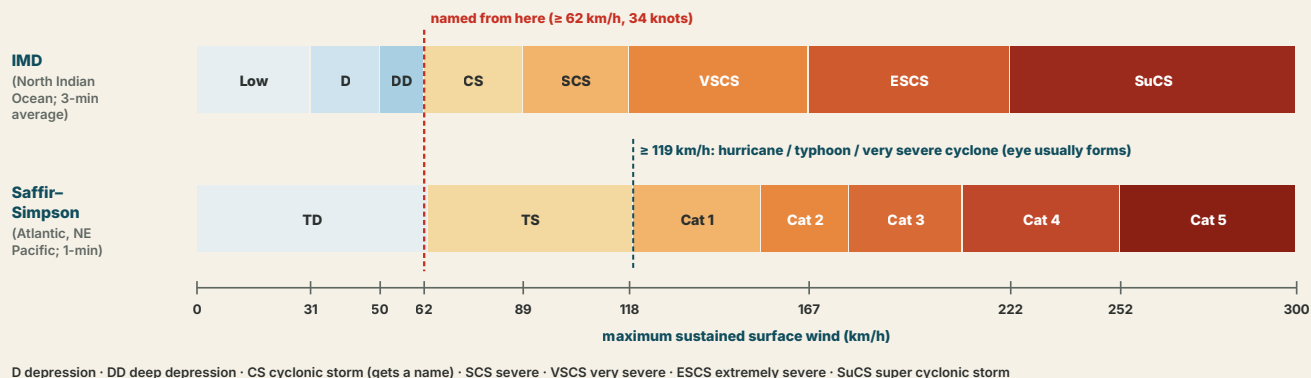


Fig. 20.24 A North Indian Ocean system gets a name when it becomes a cyclonic storm. A very severe cyclonic storm roughly equals a Category 1–2 hurricane; a super cyclonic storm is Category 4–5.

IMD CATEGORY	WIND (KNOTS)	WIND (KM/H)	TYPICAL IMPACT AND ACTION
Low pressure area	below 17	below 31	Watch
Depression (D)	17–27	31–49	Fishermen told not to venture out
Deep depression (DD)	28–33	50–61	Minor damage to loose structures
Cyclonic storm (CS)	34–47	62–88	Damage to thatched huts and branches; fishing suspended. The storm is named
Severe cyclonic storm (SCS)	48–63	89–117	Huts badly damaged, escape routes flooded; people in coastal huts moved
Very severe cyclonic storm (VSCS)	64–89	118–166	Kutcha houses damaged, rail and road disrupted; evacuation of coastal areas
Extremely severe cyclonic storm (ESCS)	90–119	167–221	Extensive damage, power and communication cut; large-scale evacuation
Super cyclonic storm (SuCS)	120 and above	222 and above	Structural damage even to strong buildings; total disruption; seawater inundation

The **Saffir–Simpson Hurricane Wind Scale** used in the Americas grades hurricanes from **Category 1** (119–153 km/h) through 2 (154–177), 3 (178–208) and 4 (209–251) to **Category 5** (252 km/h and above). Categories 3 to 5 are "major" hurricanes. The scale measures wind only, not surge or rain, which is why a "weak" storm can still be a deadly flood-maker. Australia uses its own five categories based on gusts.

How Cyclones Are Named

Names are short and easy to remember, cut confusion when two storms are active at once, and help warnings spread quickly through the media and to the public. Each WMO region has its own list and rules.

- **Atlantic and eastern Pacific:** six alphabetical lists of 21 names, alternating male and female, reused every six years. The names of very deadly or costly storms are retired (Katrina, Helene and Milton are among them). Since 2021 a supplementary list replaces the Greek alphabet in very busy years.
- **North-west Pacific:** 140 names contributed by 14 countries, many of them flowers, animals and places rather than people's names.

- **North Indian Ocean:** the **WMO/ESCAP Panel on Tropical Cyclones (PTC)**, set up in 1972, agreed in 2000 at its session in Muscat to name storms; naming began in **September 2004** (the first was **Onil**) with 64 names from eight countries. The list ran out with **Amphan** in 2020.
- The **2020 list has 169 names: 13 each from 13 countries**, Bangladesh, India, Iran, Maldives, Myanmar, Oman, Pakistan, Qatar, Saudi Arabia, Sri Lanka, Thailand, UAE and Yemen. Names are used in order, country by country down each column (the countries are in alphabetical order), starting with Nisarga (Bangladesh), then Gati (India), Nivar (Iran) and so on. A name is **used only once**; it must be neutral in politics, religion, culture and gender, inoffensive, and no longer than eight letters.
- **Who names:** **RSMC New Delhi** (IMD) names a system when it becomes a cyclonic storm. The second column ended with **Ditwah** in November 2025, so the next storms will take **Arnab** (Bangladesh) and then **Murasu** (India). India's 13 names are Gati, Tej, Murasu, Aag, Vyom, Jhar, Probaho, Neer, Prabhanjan, Ghurni, Ambud, Jaladhi and Vega.

12 Cyclones of the North Indian Ocean

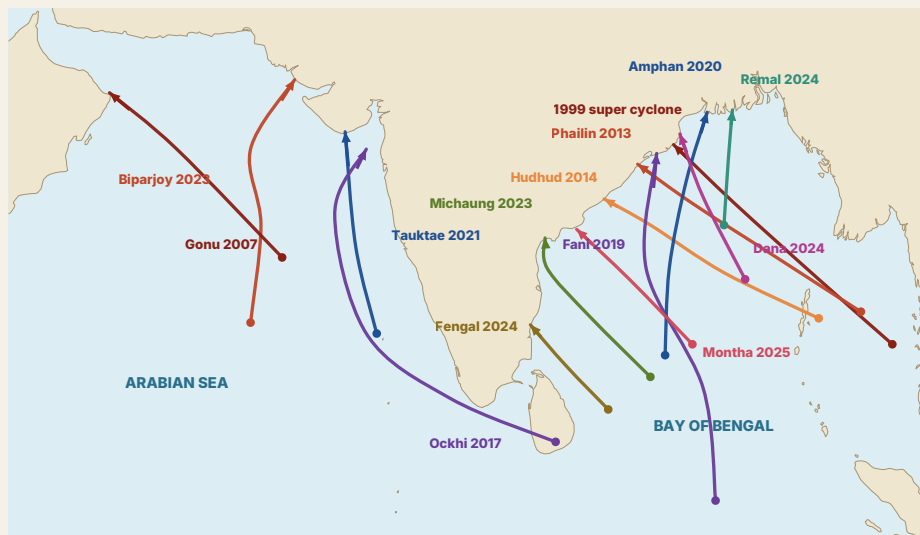
The North Indian Ocean averages about **five cyclonic storms a year**. They come in two seasons: a **pre-monsoon** peak in April–June and a stronger **post-monsoon** peak in October–December, the season of most severe storms. During the south-west monsoon itself, the strong westerlies below and the Tropical Easterly Jet above create heavy shear, and the systems that form in the monsoon trough over the narrow northern Bay cross the Odisha–Bengal coast within a day or two. They bring rain as **monsoon depressions** but rarely grow beyond that stage.

Bay of Bengal versus Arabian Sea

Over the long term, the Bay of Bengal gets about four times as many cyclones as the Arabian Sea, and its storms are more often deadly. The reasons:

- **More seedlings:** besides storms born in the Bay, the remnants of north-west Pacific typhoons often cross Myanmar and the Andaman Sea and redevelop over it. Arabian Sea storms form locally or are leftovers of Bay storms that survive the crossing of the peninsula, which few do.
- **Warmer, layered water:** the Bay is usually warmer by 1–2 °C. The Ganga, Brahmaputra, Irrawaddy, Godavari and other rivers pour so much fresh water into it that a light, low-salinity layer floats on top (surface salinity can fall to about 31 parts per thousand). This layer resists mixing, so storms cannot easily churn up cold water and keep their fuel. The Arabian Sea is saltier and mixes more readily; in its west, the Somali (Findlater) jet drives upwelling of cold water.
- **Moisture:** monsoon winds keep carrying the moisture evaporated over the Arabian Sea towards India.
- **Shape of the Bay:** its narrow, shallow, funnel-shaped head and the flat Ganga–Brahmaputra delta make surges higher and floods more deadly.

Notable Cyclones of the North Indian Ocean



THE TWO SEAS COMPARED

Bay of Bengal ~4

AS ~1

share of cyclonic storms (long-term)

Bay of Bengal

warmer, low-salinity surface layer that resists mixing; seedlings from Pacific typhoon remnants; narrow, shallow head funnels storm surge

Arabian Sea

fewer storms, cooler upwelled water in the west; but since 2001 storms are 52% more frequent and very severe ones up by about 150%

Seasons

twin peaks: April–June and October–December; few in the monsoon (strong shear)

Tracks simplified; dots mark genesis.

Fig. 20.25 Most storms form in the south and centre of the Bay of Bengal or the south-east Arabian Sea and move north-west, many recurving north-east. Tracks are simplified.

Where India is most at risk

About 8% of India's area is prone to cyclones, along a long coastline in 13 coastal states and union territories. The **east coast** takes most hits: Odisha and West Bengal for severe storms in October–November and May, Andhra Pradesh and Tamil Nadu in November–December. On the west coast, **Gujarat** is the most vulnerable state. Islands such as the Andaman and Nicobar group and Lakshadweep are exposed to both seas.

An Arabian Sea Waking Up

A study comparing 2001–2019 with 1982–2000 found that cyclone frequency in the **Arabian Sea rose by 52%** and very severe cyclones by about **150%**, while the Bay of Bengal's count fell by about 8%; Arabian Sea storms also lasted longer. The cause is the rapid warming of the Arabian Sea surface. In **2019** the Arabian Sea had a record five cyclones (Vayu, Hikka, Kyarr, Maha and Pavan), Kyarr becoming only its second super cyclonic storm after **Gonu** (2007, Oman). Ockhi (2017) raced from near Sri Lanka past Lakshadweep, killing hundreds of fishermen; **Tauktae** (2021) ran up the whole west coast; and **Biparjoy** (2023) became the longest-lived cyclone on record in the Arabian Sea.

Major Cyclones That Struck the Region

CYCLONE (YEAR)	PEAK STRENGTH	LANDFALL	WHY IT MATTERS
Bhola (Nov 1970)	ESCS	East Pakistan (now Bangladesh)	Deadliest tropical cyclone on record, roughly 3–5 lakh dead, mostly by surge
Odisha super cyclone (Oct 1999)	SuCS, about 260 km/h	Near Paradip, Odisha, 29 Oct	About 10,000 dead; led to the creation of the Odisha State Disaster Management Authority, India's first
Nargis (May 2008)	ESCS	Irrawaddy delta, Myanmar	About 1.4 lakh dead; surge across a low delta
Phailin (Oct 2013)	VSCS	Gopalpur, Odisha, 12 Oct	Near-1999 strength, but about 10 lakh people evacuated and deaths kept to a few dozen
Hudhud (Oct 2014)	ESCS	Visakhapatnam, Andhra Pradesh	Severe urban damage to a major port city

Fani (May 2019)	ESCS	Puri, Odisha, 3 May	Rare pre-monsoon storm of this strength; about 12 lakh evacuated, praised by the UN
Amphan (May 2020)	SuCS	Across the Sundarbans, between Digha (West Bengal) and Hatiya (Bangladesh), 20 May	First super cyclone in the Bay since 1999; the costliest in the North Indian Ocean
Tauktae and Yaas (May 2021)	ESCS; VSCS	Saurashtra (Gujarat); Balasore (Odisha)	Back-to-back storms on both coasts in the same month
Biparjoy (June 2023)	ESCS	Near Jakhau, Kutch, Gujarat, 15 June	About 13 days at sea; timely evacuation of about one lakh people in Gujarat
Michaung (Dec 2023)	SCS	Near Bapatla, Andhra Pradesh	Stalled off Chennai and flooded the city
Remal (May 2024)	SCS	Between Sagar Island and Khepupara (Bangladesh)	Surge in the Sundarbans; landslides and floods in the north-east
Dana (Oct 2024)	SCS	Near Bhitarkanika–Dhamra, Odisha	Mass evacuation in Odisha and West Bengal
Fengal (Nov–Dec 2024)	CS	Near Puducherry, 30 Nov	Slow-moving; extreme rain in Villupuram and Puducherry
Shakhti (Oct 2025)	SCS	Stayed over the Arabian Sea, off Oman	First named storm of 2025
Montha (Oct 2025)	SCS	Near Narsapur, south of Kakinada, Andhra Pradesh, 28 Oct	Heavy rain and crop loss in Andhra Pradesh and Telangana
Senyar and Ditwah (Nov–Dec 2025)	CS	Sumatra (Strait of Malacca); Sri Lanka, then along the Tamil Nadu coast	Weak in wind but catastrophic floods: over a thousand dead in Sumatra and over 600 in Sri Lanka

As of September 2026, the North Indian Ocean had seen only depressions and deep depressions in 2026, with no named cyclonic storm. Several monsoon systems still caused deadly floods and lightning in eastern India.

2025: weak winds, huge losses. The 2025 North Indian Ocean season was the costliest on record. Its storms were modest on the wind scale, yet Senyar and Ditwah, together with other systems in the region, caused floods and landslides across Sumatra, southern Thailand, Malaysia and Sri Lanka. They underline that the intensity category describes wind only: slow, rain-laden storms over steep, crowded terrain can be far deadlier than their category suggests.

13

Managing Cyclones in a Warming World

India has turned cyclones from mass-casualty events into largely managed ones. The 1999 super cyclone killed about 10,000 people; storms of similar strength since 2013 have killed a few dozen each, thanks to better forecasts, early evacuation and shelters. Losses to housing, crops, power and livelihoods, however, keep rising as coasts fill up with people and assets.

Forecasts and Warnings

IMD's cyclone warning division and RSMC New Delhi track storms with geostationary satellites (INSAT-3D, 3DR and 3DS), Doppler weather radars along both coasts, ocean buoys, ships and numerical models, and issue advisories to the 13 PTC countries. Track forecasts have improved sharply: the error in landfall forecasts a day ahead has fallen from well over 100 km in the early 2000s to well under 100 km today.

IMD's four-stage cyclone warning

STAGE	WHEN ISSUED	COLOUR	PURPOSE
Pre-cyclone watch	When a depression forms and the coast may face adverse weather; about 72 hours ahead	—	Early alert to top officials and disaster managers
Cyclone alert	At least 48 hours before adverse weather begins	Yellow	Warns of the coming storm; ports and fishermen alerted
Cyclone warning	At least 24 hours ahead; gives the expected landfall time and place	Orange	Evacuation and response begin
Post-landfall outlook	About 12 hours before landfall	Red	Weather expected inland after the storm crosses the coast

PRELIMS POINTER · IMD'S COLOUR-CODED WARNINGS (MAINS 2022)

IMD's general impact-based weather warnings use four colours: **Green**: no warning, no action needed. **Yellow**: be aware; severe weather possible, stay updated. **Orange**: be prepared; severe weather likely, with disruption to transport and power and risk to life and property. **Red**: take action; extremely severe weather certain, evacuation and protective measures needed. The colour reflects expected **impact**, not just the wind or rain amount. Alerts now also reach phones in danger zones through the Common Alerting Protocol platform (SACHET).

From Relief to Preparedness

- **National Cyclone Risk Mitigation Project (NCRMP)**: a World Bank-assisted project run by NDMA under the Ministry of Home Affairs, begun in 2011 with Andhra Pradesh and Odisha and extended from 2015 to Gujarat, Maharashtra, Goa, Karnataka, Kerala and West Bengal. It funds early-warning dissemination systems in coastal villages, multi-purpose cyclone shelters, all-weather roads and bridges to them, saline embankments and underground power cabling.
- **NDMA guidelines** on cyclone management (2008) set the framework: hazard mapping, coastal zone rules, cyclone-resistant building codes, shelterbelts and community training.
- **Nature-based defences**: mangroves (Bhitarkanika, the Sundarbans, Pichavaram) and casuarina shelterbelts absorb surge and wind. The **MISHTI** scheme (2023) supports mangrove planting along the coast.
- **Mission Mausam** (approved September 2024) aims to make India "weather-ready and climate-smart" with more radars, better models and, in time, weather modification research.

The Odisha model

After about 10,000 people died in the 1999 super cyclone, Odisha built a system that the UN now holds up as a model. It set up the **Odisha State Disaster Management Authority** (1999) and a trained rapid action force (ODRAF), built hundreds of multi-purpose cyclone shelters run by village committees, installed sirens and early-warning towers along the coast, and rehearsed evacuation with mock drills. The guiding idea is "**zero casualty**": move everyone out of harm's way before landfall. In Phailin (2013) about 10 lakh people were evacuated and deaths stayed in the dozens; in Fani (2019) about 12 lakh were moved within a day or two. Gujarat's evacuation before Biparjoy (2023) followed the same approach.



Fig. 20.26 Evacuees in a multi-purpose cyclone shelter at Basudevapur, Bhadrak district, Odisha.

Cyclones and Climate Change

Sea-surface temperature rise (Mains 2024) is the main link between global warming and cyclones. The broad findings of the IPCC's Sixth Assessment and later studies:

- The **total number** of tropical cyclones worldwide is not projected to rise, and may fall slightly.
- The **share of the most intense storms** (Category 4–5) has likely risen over the past four decades and is projected to keep rising; their peak winds increase with warmer oceans.
- **Rain rates** are increasing, because warmer air holds about 7% more water vapour per degree Celsius.
- **Rapid intensification** is becoming more common; storms are slowing down and reaching peak strength further poleward; and **sea-level rise** makes every surge reach further inland.
- Regionally, the warming Arabian Sea is producing more and stronger storms, and El Niño and the Indian Ocean Dipole modulate the numbers from year to year (Chapter 22).

Recent Extreme Storms Elsewhere

- **Beryl** (July 2024): the earliest Category 5 hurricane on record in the Atlantic, fed by record-warm seas.
- **Helene** (September 2024): a Category 4 landfall in Florida, then catastrophic floods in the Appalachians; about 250 deaths, the most on the US mainland since Katrina (2005).
- **Milton** (October 2024): intensified from a tropical storm to a Category 5 in about a day and a half over the Gulf of Mexico, one of the fastest rates on record; it came ashore near Sarasota, Florida.
- **Melissa** (October 2025): reached about 300 km/h with a central pressure near 892 hPa and struck Jamaica on 28 October as a Category 5, the strongest hurricane ever to hit the island and one of the most intense Atlantic hurricanes on record.
- **2026**: a strong El Niño has suppressed the Atlantic season (only weak tropical storms up to September), while the north-west Pacific has been active from an unusually early start in January, with several intense typhoons.

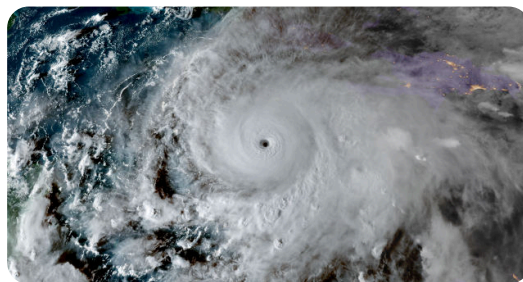


Fig. 20.27 Hurricane Melissa, a Category 5 storm, south of Jamaica on 26 October 2025 (NOAA satellite image).

USING THIS CHAPTER IN MAINS

Cyclones, tornadoes and cloudbursts are regular in GS Paper I, and GS Paper III disaster questions often use cyclones as the example. A good answer:

- opens with a crisp definition and a labelled sketch: a cyclone cross-section (eye, eyewall, rain bands, inflow and outflow), a recurvature track, a storm-surge profile or a supercell;
- explains the mechanism in a chain: warm water → evaporation → latent heat → falling pressure → stronger inflow, and lists the six conditions with figures (26.5 °C, 50–60 m, 5° latitude, low shear);
- uses Indian examples and current facts: the Bay–Arabian Sea contrast and the 52% rise in Arabian Sea cyclones, Phailin and Fani evacuations, the 169-name list, IMD's colour codes, lightning and heatwaves notified as disasters in 2026;
- closes with management and climate change: NCRMP, the Odisha model, mangroves, impact-based warnings, rapid intensification and sea-level rise.



Previous Year Questions

Prelims

2020

Consider the following statements:

1. Jet streams occur in the Northern Hemisphere only.
2. Only some cyclones develop an eye.
3. The temperature inside the eye of a cyclone is nearly 10°C lesser than that of the surroundings.

Which of the statements given above is/are correct?

☐ a 1 only

☐ b 2 and 3 only

☒ c 2 only

☐ d 1 and 3 only

Answer: (c). Jet streams blow in both hemispheres, and the eye is warmer, not colder, than its surroundings.

2015

In the South Atlantic and South-Eastern Pacific regions in tropical latitudes, cyclone does not originate. What is the reason?

☒ a Sea surface temperatures are low

☐ b Inter-Tropical Convergence Zone seldom occurs

☐ c Coriolis force is too weak

☐ d Absence of land in those regions

Answer: (a). Cold currents and upwelling keep these waters below the 26.5 °C threshold.

2015

"Each day is more or less the same, the morning is clear and bright with a sea breeze; as the Sun climbs high in the sky, heat mounts up, dark clouds form, then rain comes with thunder and lightning. But rain is soon over." Which of the following regions is described in the above passage?

☐ a Savannah

☒ b Equatorial

☐ c Monsoon

☐ d Mediterranean

Answer: (b). Daily afternoon convectional thunderstorms are the signature of the equatorial climate.

2013

During a thunderstorm, the thunder in the skies is produced by the

1. meeting of cumulonimbus clouds in the sky
 2. lightning that separates the nimbus clouds
 3. violent upward movement of air and water particles
- Select the correct answer using the codes given below.

☐ a 1 only

☐ b 2 and 3

☐ c 1 and 3

☒ d None of the above produces the thunder

Answer: (d). Thunder is the shock wave of air expanding explosively when lightning heats it.

2002 Consider the following climatic and geographical phenomena:

1. Condensation
2. High temperature and humidity
3. Orography
4. Vertical wind

Thunder-cloud development is due to which of these phenomena?

a 1 and 2

b 2, 3 and 4

c 1, 3 and 4

d 1, 2, 3 and 4

Answer: (d). Moisture, heat, lift (orographic or convective) and condensation all go into a cumulonimbus.

2001 Which of the following weather conditions is indicated by a sudden fall in barometer reading?

a Stormy weather

b Calm weather

c Cold and dry weather

d Hot and sunny weather

Answer: (a). A rapid pressure fall signals an approaching low and storm.

1995 Willy Willy is

a a type of tree grown in temperate regions

b a wind that blows in a desert

c a tropical cyclone of north-west Australia

d a kind of common fish found near Lakshadweep islands

Answer: (c). The old Australian name for a tropical cyclone off the north-west coast.

Mains

2026

GS I · 10 MARKS

What is the Fujiwhara effect? Explain its impact on the movement and intensity of tropical cyclones.

Approach: Define the effect with a sketch of two storms orbiting a common centre (Fig. 20.21 C); explain erratic tracks, merger or absorption, and changes in intensity through shear and dry air; give a north-west Pacific or North Indian Ocean example and the forecasting challenge (Section 10).

2024

GS I · 15 MARKS

What is a twister? Why are the majority of twisters observed in areas around the Gulf of Mexico?

Approach: Define a tornado and its formation from supercells; then explain the Gulf's moisture, the dry-air lid, frontal lift, jet-stream shear and flat terrain of Tornado Alley with a map (Section 05, Fig. 20.13).

2024

GS I · 10 MARKS

What is sea surface temperature rise? How does it affect the formation of tropical cyclones?

Approach: Define SST rise and its causes; link to the 26.5 °C threshold, ocean heat content, rapid intensification, rain rates and the Arabian Sea trend (Sections 07, 10 and 13).

2024

GS I · 10 MARKS

What is the phenomenon of 'cloudbursts'? Explain.

Approach: IMD definition (100 mm an hour over 20–30 km²), orographic mechanism, Himalayan examples such as Kedarnath 2013 and Kishtwar 2025, effects and the need for dense radars and warnings (Section 04).

2022

GS I · 10 MARKS

Discuss the meaning of colour-coded weather warnings for cyclone prone areas given by India Meteorological Department.

Approach: Explain the green–yellow–orange–red impact-based codes and the four-stage cyclone warning, with the action expected at each level and an example such as Biparjoy or Fani (Section 13).

2014

GS I

Tropical cyclones are largely confined to the South China Sea, Bay of Bengal and the Gulf of Mexico. Why?

Approach: Warm, deep water on the western sides of oceans, enough Coriolis force, seedling disturbances, low shear and the thermal equator's northward position; add a basin map (Sections 07–08).

2013

GS I

The recent cyclone on the east coast of India was called 'Phailin'. How are tropical cyclones named across the world? Elaborate.

Approach: Why storms are named; WMO regional bodies and RSMCs; Atlantic alphabetical lists and retirement; the North Indian Ocean country-wise list of 2004 and the 169-name list of 2020; note Phailin was a Thai name (Section 11).

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