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UPSC CSE MAINS

GEOGRAPHY OPTIONAL

PAPER I

Climatology Notes

The complete Climatology section of Paper I — atmosphere and heat budget, pressure, winds and circulation, moisture and precipitation, air masses and storms, climatic classification, and climatic change, with previous year questions.

Compiled by Arvind KrS

HEAT BUDGET · ATMOSPHERIC CIRCULATION · MONSOONS AND JET STREAMS · CYCLONES · CLIMATIC CLASSIFICATION · CLIMATIC CHANGE

30	6	115	139
Chapters	Units	Previous year questions	Diagrams and figures



IN THIS BOOK

01 The Atmosphere and Its Heat Budget

02 Pressure, Winds and Atmospheric Circulation

03 Moisture, Stability and Precipitation

04 Air Masses, Fronts and Storms

05 Climatic Classification and World Climates

06 Climatic Change and Applied Climatology

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Geography Optional — Climatology

Paper I · Physical Geography: Climatology

Mains 2027 Edition · Compiled October 2026

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Questions or corrections: support@lotusarise.com

How to read these notes

Every chapter is marked against the questions UPSC has actually asked on it, so the points that matter most stand out on the first read and are quick to find at revision.

Tropical cyclones form only over warm seas, roughly 26–27 °C and above, and not within about 5° of the equator.

Yellow marker: key point. A point that carries the ideas UPSC has asked about in this chapter. Read these first, and make sure each one is in your answer.

Albedo is the share of incoming solar radiation that a surface reflects back to space.

Blue marker: definition. The cleanest definition of a term, ready to open an answer with.

Winds are shaped by the **pressure gradient, Coriolis force and friction**.

Saffron underline: PYQ term. A key term or phrase that appears in this chapter's previous year questions.

Properties of an Air Mass

PYQ 2025 · 2024 · 2022 +4

PYQ tag on a heading. The years in which UPSC asked about this section. Sections without a tag are background or linking material.

PYQ RADAR **10** questions Last asked **2025**

PYQ radar. At the start of each chapter: how many times the topic has been asked, and how recently. The contents page shows the same count for every chapter.

Suggested method. First read: the whole chapter. Revision: the yellow and blue marks, the tagged headings and the PYQ list at the end of the chapter. Last week before Mains: the PYQ list alone, answering each question in your head from the marked points.

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UNIT 01 | 5 CHAPTERS

The Atmosphere and Its Heat Budget

Heat budget of the earth; temperature belts of the world.

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GEOGRAPHY OPTIONAL | PAPER I · CLIMATOLOGY

Heat Budget of the Earth: Insolation, Albedo and Energy Balance

PYQ RADAR **3** questions Last asked **2025** 2025 · 2022 · 2016

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01	Insolation	02	Atmospheric Depletion of Solar Radiation
03	Heat Budget of the Earth and Atmosphere	04	Heat Transfer Processes
05	Short-Term Variations: Diurnal and Seasonal Heat Budgets	06	Latitudinal Heat Balance and Poleward Transfer
07	Significance	08	Previous Year Questions

- **Insolation** (*incoming solar radiation*) is the short-wave radiant energy from the sun received by the Earth. It supplies **more than 99.9%** of the energy that heats the planet and **drives all atmospheric and oceanic motion**.
- The **heat budget (energy balance)** is the long-term **equality between the solar energy absorbed by the Earth–atmosphere system and the long-wave energy it radiates back to space**.
  - Because of this balance, the global mean surface temperature stays near **15 °C** instead of warming or cooling year after year.
- The balance holds **for the planet as a whole, not for each latitude or season**. The resulting **surplus in the tropics and deficit near the poles** is what sets the winds and ocean currents in motion.

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01 Insolation PYQ 2016

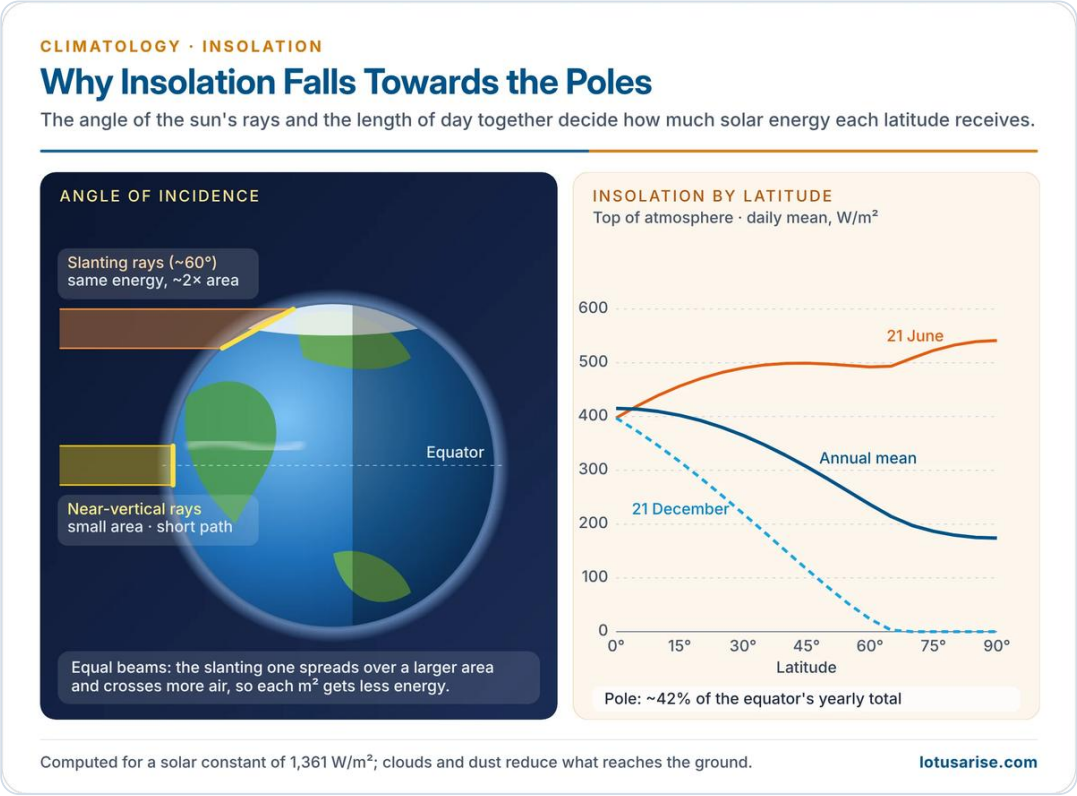
Solar Radiation and the Solar Constant

- The sun (surface about **5,800 K**) radiates as a near **black body** with peak emission at about **0.5 µm** (visible light).
  - About **half** of the energy arrives as **infrared**, **40–45%** as **visible light** and **under 10%** as **ultraviolet**.
- The Earth (about **288 K**) radiates at much longer wavelengths, peaking near **10 µm**. Hence:
  - **Solar radiation = short-wave**
  - **Terrestrial radiation = long-wave**
  - This difference is the basis of the **greenhouse effect**.
- **Solar constant** (total solar irradiance) is the energy received per unit area **perpendicular to the sun's rays at the top of the atmosphere** at the Earth's mean distance from the sun:
  - about **1,361 W/m²** (about **1.96 cal/cm²/min**, close to the classical "two langleys per minute")
  - spread over the whole sphere (area four times the intercepting disc), this gives a **global mean of about 340 W/m²**
- It is **not quite constant**: it rises by only about **0.1%** at the peak of the **11-year sunspot cycle**, too little on its own to explain modern warming.
- The Earth intercepts less than **one two-billionth** of the sun's output, yet that is the **power source for weather, the hydrological cycle and photosynthesis**. Coal, oil and wood are stored solar energy.

Factors Controlling Insolation

- **Angle of incidence (sun's altitude):**
  - A **vertical beam** falls on the **smallest area**, so energy per unit area is highest.
  - An **oblique beam** spreads over a larger area and **travels a longer path through the atmosphere**, losing more energy by scattering, reflection and absorption.
  - The angle depends on **latitude, season and time of day**: midday sun is stronger than morning or evening sun, and summer sun stronger than winter sun.
- **Duration of daylight:**
  - Day length is **12 hours at the equator** throughout the year.
  - Away from the equator it varies with the season, reaching **24 hours at the polar circles** at the solstice and **six months at the poles**.
  - **Long polar summer days** partly offset the low sun.
- **Distance between earth and sun:**
  - At **perihelion (about 3 January, 147 million km)** the Earth receives about **7% more** insolation than at **aphelion (about 4 July, 152 million km)**.
  - The northern winter therefore falls when the Earth is closest. Distance matters far less than angle and day length.
- **Solar output:** sunspot and faculae cycles cause small variations. Longer-term orbital (Milankovitch) changes matter over tens of thousands of years.

- **Transparency of the atmosphere:**
  - **Clouds, water vapour, dust and smoke** deplete the beam.
  - Clear-sky deserts and **high plateaux** receive more insolation at the surface than humid lowlands at the same latitude.
- **Aspect and slope of land:** in the northern hemisphere, **south-facing (adret) slopes** receive more insolation than north-facing (ubac) slopes. In Himalayan valleys this sets the pattern of settlement and cultivation.



Spatial and Seasonal Distribution

- **Annual insolation** at the top of the atmosphere **falls from the equator to the poles**, but the poles still receive about **40%** of the equatorial amount:

LATITUDE	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
Annual insolation (% of equator)	100	99	95	88	79	68	57	48	43	42

- **Seasonal swing grows with latitude:**
  - The **tropics** get two maxima a year (two overhead suns) and little seasonal change.
  - Between the tropics and the polar circles, the maximum and minimum fall at the **summer and winter solstices**.
- **At the June solstice**, the **North Pole receives more daily insolation at the top of the atmosphere than the equator** (24 hours of daylight). Ice and snow reflect much of it, so the surface warms little.

- **At the surface, the maximum is subtropical, not equatorial:**
  - The highest annual totals fall near **20–30° N and S** in the **cloud-free subtropical deserts** (Sahara, Arabia, Thar), where the descending air of the subtropical highs keeps skies clear.
  - The **cloudy equatorial belt** receives less at the surface than its sky position suggests.
- **Continents receive more than oceans** at the same latitude, because there is less cloud over land.
- **India:**
  - The highest insolation is received over **western Rajasthan, Gujarat and Ladakh**: clear dry air there, and in Ladakh high altitude as well.
  - The lowest is over the **north-east and the Western Ghats during the monsoon**, when cloud cover cuts direct sunshine.
  - This geography underlies the siting of large **solar parks** such as **Bhadla (Rajasthan)**.

02 Atmospheric Depletion of Solar Radiation

- On its way down, part of the solar beam is **scattered, reflected or absorbed**:
  - **Scattering:**
    - Gas molecules and fine particles, smaller than the wavelength of light, scatter **shorter wavelengths far more** than longer ones. This is **Rayleigh scattering**, which varies with $1/\lambda^4$.
    - It produces the **blue sky**, and the **red and orange sun** at dawn and dusk, when the path is longest.
  - **Diffuse reflection (diffusion):**
    - Particles **larger than the wavelength**, such as cloud droplets and coarse dust, scatter all colours equally (**Mie or non-selective scattering**).
    - It makes **clouds white**, haze grey and the **sun white through fog**.
    - It also gives **twilight and light in shade**.
  - **Absorption:**
    - **Ozone and oxygen** absorb ultraviolet shorter than about 0.3 µm.
    - **Water vapour and carbon dioxide** absorb in the infrared.
    - Dust and clouds absorb a little.
    - The atmosphere absorbs about **one-fifth to one-quarter** of the incoming beam directly.
  - **Reflection:** part of the beam bounces back to space without heating anything. The reflectivity of a surface is its **albedo**.

Albedo

SURFACE	ALBEDO (%)	SURFACE	ALBEDO (%)
Fresh snow	80–85	Forest	5–15

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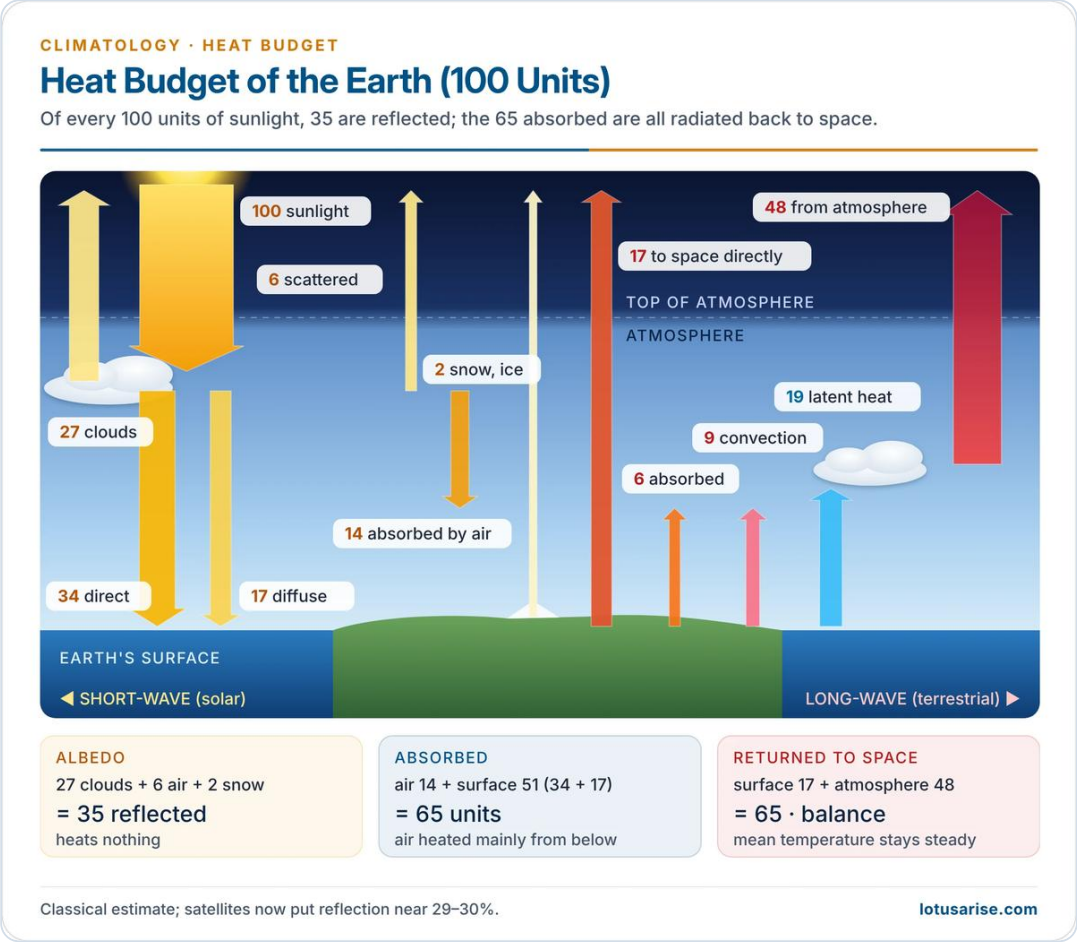
SURFACE	ALBEDO (%)	SURFACE	ALBEDO (%)
Old snow	50–60	Water, sun high	3–5
Thick cloud	70–80	Water, sun low	50–80
Sand, desert	20–40	Grassland	20–25
Dry soil	15–25	Asphalt, dark city surfaces	5–10

- **Planetary albedo** is about **0.29–0.30**. Satellites (NASA's CERES) show the Earth reflects about **29–30%** of incoming sunlight.
  - Most of this reflection comes from **clouds**, then from the air and aerosols, and only a small part from the surface.
  - Older textbook estimates of 34–35% have been revised downward.
- **Albedo feedbacks:** when **sea ice and snow** melt, dark ocean and land are exposed, more energy is absorbed and warming accelerates. This **ice–albedo feedback** is a main reason the **Arctic is warming about three to four times faster** than the global average.

03 Heat Budget of the Earth and Atmosphere PYQ 2025

Classical Model (100 Units of Insolation)

- Take **100 units** of insolation at the top of the atmosphere:
  - **35 units are reflected to space** without heating anything. This is the **albedo**:
    - **27 units** from cloud tops
    - **6 units** scattered back by air and dust
    - **2 units** from snow and ice
  - **14 units are absorbed by the atmosphere** (water vapour, ozone, dust and clouds).
  - **51 units are absorbed by the surface**: **34 units** as direct sunlight and **17 units** as diffuse skylight.
- The surface **returns its 51 units**:
  - **17 units** escape **directly to space** through the **atmospheric window** (8–13 μm).
  - **34 units** are absorbed by the atmosphere:
    - **6 units** by direct absorption of long-wave radiation
    - **9 units** by **conduction, convection and turbulence** (sensible heat)
    - **19 units** as **latent heat of condensation**
- The atmosphere, holding **14 + 34 = 48 units**, radiates them to space.
- **Balance:** 17 (surface) + 48 (atmosphere) = **65 units out**, which equals the **65 units absorbed**.



- **What the model shows:**
  - The **atmosphere is heated mainly from below**: it absorbs only 14 units of sunlight directly but 34 units from the ground. This explains why temperature normally **falls with height** in the troposphere.
  - **Latent heat** is the biggest single channel of heat from surface to air. Evaporation over oceans and condensation in clouds act as a planetary heat engine.
  - The surface and atmosphere **trade heat back and forth** many times before it leaves. This is why the surface is about **33 °C warmer** than an airless Earth of the same albedo would be.

Modern Satellite-Era Budget

- Satellite measurements (CERES) and surface networks give a more detailed budget. The values below, in **W/m²** for the early 21st century, are those assessed by the **IPCC Sixth Assessment Report (2021)**:

FLUX	W/M²	% OF INCOMING
Incoming solar at top of atmosphere	340	100
Reflected to space (clouds, air, surface)	100	29
Absorbed by the atmosphere	80	24

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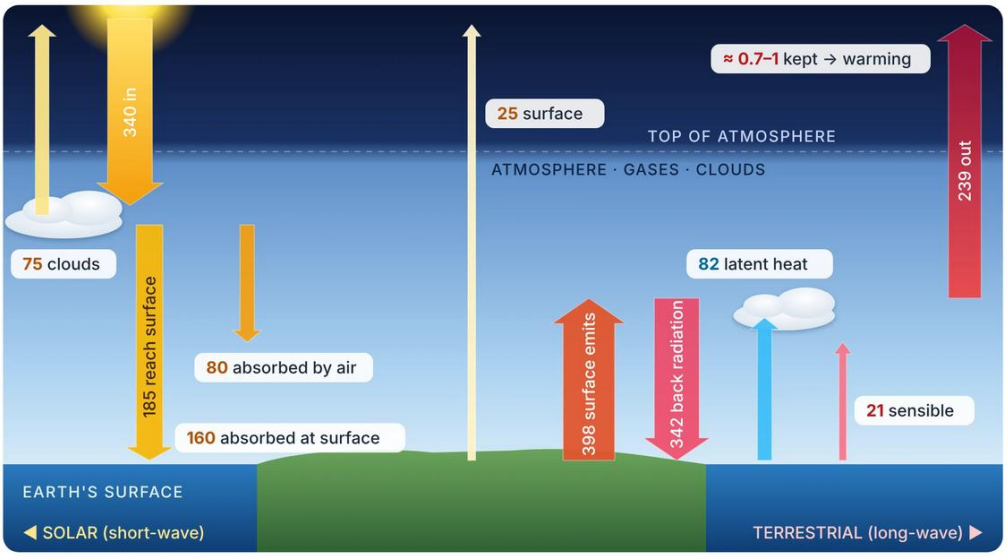
FLUX	W/M²	% OF INCOMING
Absorbed by the surface	160	47
Emitted by the surface (long-wave)	398	—
Back radiation from atmosphere to surface	342	—
Latent heat flux (evaporation)	82	—
Sensible heat flux	21	—
Outgoing long-wave radiation at top of atmosphere	239	—
Net imbalance (absorbed in the climate system)	about 0.7	—

- **The surface emits far more (398) than it receives from the sun (160)**, because it also receives **342 W/m² of back radiation**. This is the **greenhouse effect** in numbers.
  - Water vapour, CO_2, methane, nitrous oxide and clouds absorb long-wave radiation and re-emit much of it downward.
- **Earth's energy imbalance:** the planet now absorbs more than it emits.
  - Satellite and ocean-float records show the imbalance **roughly doubled between 2005 and 2019**, to about **1 W/m²** (Norman Loeb and colleagues, 2021).
  - The causes are rising greenhouse gases and **fewer reflective clouds and less sea ice**.
  - About **90%** of the surplus heat goes into the **oceans**.

CLIMATOLOGY · HEAT BUDGET

Earth's Energy Budget in the Satellite Era

Global mean flows in W/m² for the early 21st century; the planet now keeps a small surplus each year.



TOP OF ATMOSPHERE
in 340 − out 100 − 239
≈ +1 W/m² kept
planetary albedo ≈ 29%

GREENHOUSE EFFECT
160 solar + 342 back radiation
surface emits 398
≈ 33 °C warmer than no air

SURFACE TO AIR
latent 82 + sensible 21
evaporation leads
the water cycle lifts heat

Values as assessed by the IPCC Sixth Assessment Report (2021); the imbalance has grown to about 1 W/m².

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ASPECT	CLASSICAL 100-UNIT MODEL	MODERN SATELLITE BUDGET
Basis	Early estimates (mid-20th century)	CERES satellites, surface networks, ocean floats
Planetary albedo	35%	about 29%
Direct atmospheric absorption	14%	about 24%
Surface absorption	51%	about 47%
Greenhouse back radiation	Implicit	Explicit (342 W/m²)
Balance	Exact	Small positive imbalance (warming)

04 Heat Transfer Processes

- **Radiation:**
  - Transfer by electromagnetic waves, needing no medium.
  - Sun to earth is **short-wave;** earth to atmosphere and space is **long-wave**.

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- **Conduction:**
  - Transfer by contact, from warmer to cooler.
  - It heats only the **lowest few metres of air** by day and chills them at night, so air, a poor conductor, warms slowly by this route.
- **Convection:**
  - **Vertical transfer** by rising warm air and sinking cool air.
  - It carries heat and moisture up through the **troposphere** and builds cumulus clouds.
- **Advection:**
  - **Horizontal transfer** by winds and ocean currents.
  - It dominates day-to-day temperature change in **middle latitudes**.
  - In India the hot, dry **loo** winds of May–June bring advected heat across the northern plains.
- **Latent heat transfer:**
  - Energy is absorbed in **evaporation** and released in **condensation**.
  - It moves heat both upward and poleward.

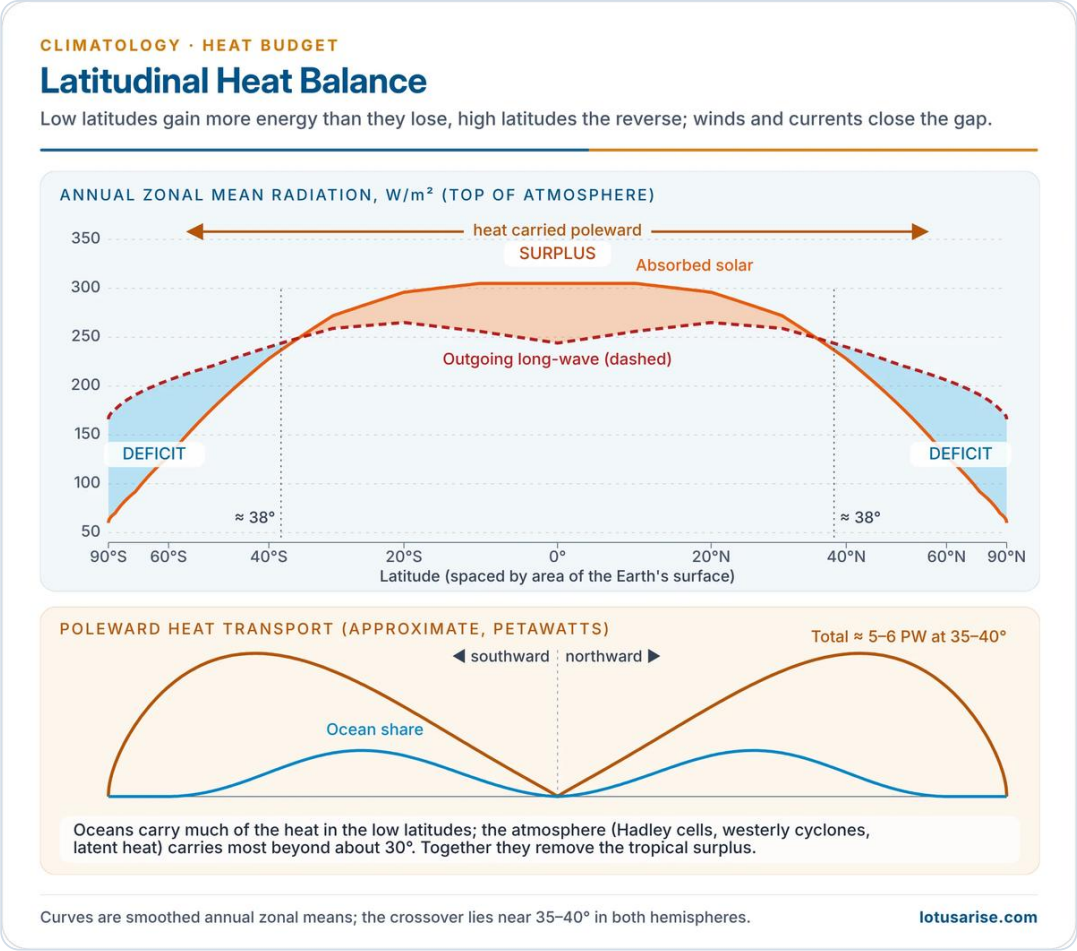
05 Short-Term Variations: Diurnal and Seasonal Heat Budgets

- **Daily cycle:**
  - Insolation peaks at **noon**, but the surface keeps gaining more than it loses until about **2–3 p.m.** So the **maximum temperature lags** behind the sun.
  - The **minimum** comes **just before sunrise**, after a night of net radiative loss.
- **Seasonal cycle:**
  - The surplus peaks after the summer solstice. The **hottest month lags** (July on land, August over oceans in the northern hemisphere) because land and especially water store heat.
  - In India, **May** (before the monsoon clouds) is hotter than June or July over much of the north. Clouds and rain then cut insolation and spend energy on evaporation.
- **Clouds and moisture** cut both ways:
  - **Cloudy days** are cooler, because clouds reflect insolation.
  - **Cloudy nights** are warmer, because clouds return long-wave radiation.
  - This is why **deserts have the largest daily ranges**: clear skies and dry air allow strong heating by day and rapid radiative cooling at night.
- These **short-term imbalances** between receipt and loss of energy produce the daily and seasonal march of temperature. They also set up **temperature inversions** on still, clear nights.

06 Latitudinal Heat Balance and Poleward Transfer

- **Between about 35–40° N and S**, the absorbed solar energy **exceeds** the outgoing long-wave radiation, giving a **surplus**. **Poleward of these latitudes** outgoing radiation exceeds absorption, giving a **deficit**.

- The tropics do not grow ever hotter, nor the poles ever colder, because **heat is carried poleward**:
  - **Atmospheric circulation** (Hadley cells, mid-latitude cyclones and anticyclones, and movement of latent heat) carries most of it, especially beyond about **30° latitude**.
  - **Ocean currents** (the Gulf Stream, the Kuroshio) carry a large share in the **low latitudes**.
  - The total transport peaks near **35–40°**, at roughly **5–6 petawatts** in each hemisphere. This is the zone of the **westerlies and frontal cyclones**.
- This **energy imbalance is the ultimate driver** of the **general circulation of the atmosphere**, the **pressure belts** and the planetary winds.



07 Significance

- The heat budget explains:
  - the **global mean temperature** and the **natural greenhouse effect**
  - the **vertical temperature structure** of the troposphere, heated from below
  - the **temperature belts**, pressure belts, winds and ocean currents, through latitudinal imbalance
- It is the **framework for climate change**:
  - Any change in **albedo** (ice, clouds, aerosols), **greenhouse gases** or **solar input** alters the balance.
  - The climate then warms or cools until a **new equilibrium** is reached.

- **Applied relevance:** solar-energy planning, urban heat islands (dark low-albedo surfaces), and crop and water planning, through evapotranspiration.

Previous Year Questions

2025	Examine the distribution and balance of energy in the Earth's atmosphere system.
2022	Describe how short term variations in temperature are related to the processes of receiving energy from the sun to the Earth's surface and dissipating it to the atmosphere.
2016	Differentiate between insolation and temperature and explain anomalous temperature.

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UNIT 02 | 8 CHAPTERS

Pressure, Winds and Atmospheric Circulation

Temperature and pressure belts of the world; Atmospheric circulation; Planetary and local winds; monsoons and jet streams.

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Origin of Monsoon: Classical, Air–Mass, Dynamic and Modern Theories

PYQ RADAR **10** questions Last asked **2026** 2026 ×2 · 2020 · 2014 · 2013 · 2008 · 2006 · 2002 · 1999 · 1994

CONTENTS

01 Defining the Monsoon
02 Classical Theories
03 Upper-Air Theories
04 Teleconnections: Ocean–Atmosphere Theories
05 Synthesis and the Changing Monsoon
06 Previous Year Questions

- A **monsoon** is a **seasonal reversal of the prevailing wind**, bringing moist, onshore air and heavy rain in summer and dry, offshore air in winter. The word comes from the Arabic *mausim* ("season"), used by Arab sailors for the winds of the Arabian Sea that blow from the south-west for about six months and from the north-east for the rest of the year.
- The **ideal monsoon** is that of **South and South-East Asia**, where the wind turns through almost **180°**; the **Indian monsoon** supplies about three-quarters of India's annual rainfall (June–September normal: 868.6 mm).
- No single cause explains it. Explanations have moved from land–sea heating (thermal) to the seasonal shift of planetary belts and the ITCZ (dynamic), then to the upper air (jet streams, Tibetan Plateau) and ocean–atmosphere teleconnections (ENSO, IOD, MJO). Today the monsoon is seen as one regional face of a **global monsoon** tied to the annual migration of the tropical rain belt.

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01 Defining the Monsoon

PYQ 2026 · 2020 · 2014 +6

Criteria and the Global Monsoon

PYQ 2026

- **Wind-based definition: Colin Ramage (1971).** A region is monsoonal if:
  - the **prevailing wind shifts by at least 120°** between January and July
  - the prevailing direction is steady, occurring at least 40% of the time in each month
  - the mean wind exceeds 3 m/s in at least one of the months
  - fewer than one cyclone–anticyclone alternation occurs every two years in either month
  - Only parts of **Asia, Africa and northern Australia** qualify, roughly between 35°N and 25°S and from 30°W to 170°E.
- **Rain-based definition: Bin Wang and Qinghua Ding (2008).** The **global monsoon** domain is where the local-summer minus local-winter rainfall is large (the **IPCC (2021)** uses more than 2.5 mm/day) and most of the year's rain falls in summer. This brings the American monsoons into the family.
- The **IPCC Sixth Assessment Report (2021)** recognises **six regional monsoons**: South and South-East Asian, East Asian, West African, North American, South American and Australian–Maritime Continent. All are linked to the seasonal swing of the ITCZ and the Hadley circulation.

MONSOON	SUMMER FLOW	WINTER FLOW	DISTINCTIVE FEATURE
South Asian	South-west, cross-equatorial	North-east, dry	Strongest; Himalaya–Tibet barrier and heat source
East Asian	Southerly to south-westerly; *Meiyu–Baiu* front	Cold north-westerly from Siberian High	Strong, cold **winter monsoon**
West African	South-westerly from Gulf of Guinea	Dry north-easterly **Harmattan**	Sahel rainfall highly variable
Australian	North-westerly	South-east trades	Northern Australia only
North American	Gulf of California moisture	Westerly, dry	Mexico, Arizona; weak wind reversal

Pseudo-Monsoon

- A **pseudo-monsoon** (**monsoon tendency**) is a region with **some seasonal reversal or summer rain peak** caused by unequal heating of land and sea, but **without the full monsoon**: the reversal is partial, the summer flow shallow and short, and summer rain is not dominant. Typical areas:
  - **West Africa** (Guinea coast) and **East Africa with Madagascar**
  - Northern Australia
  - Eastern and south-eastern USA, with summer southerlies from the Gulf of Mexico

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  - Western and central Europe, where cool, moist westerlies return in early summer (the "European monsoon")

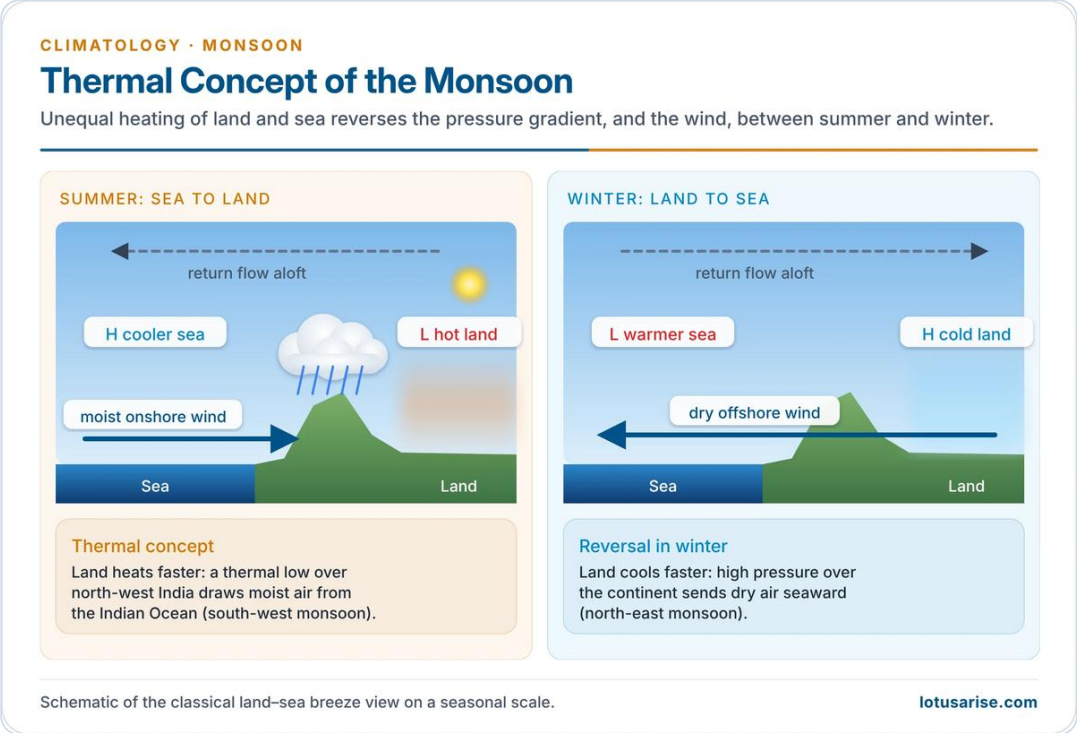
- **Why weaker than Asia:** smaller or narrower land masses, no high plateau acting as an elevated heat source, no east–west mountain wall to block polar air, cold currents offshore, and desert or ocean on the poleward side.
- **Evaluation:** the label is a classical, wind-based one. By the rain-based definition, the West African, Australian and North American systems are **true monsoons**; the IPCC treats them as such and keeps no pseudo-monsoon class.

02 Classical Theories

Thermal Concept: Edmond Halley (1686)

- **Proponent: Edmond Halley (1686)**, supported later by **Julius Hann** and others, who saw the monsoon as a **land and sea breeze on a seasonal scale**.
- **Assumption:** land heats and cools faster than sea, so pressure over land swings more between seasons.
- **Summer:** Asia heats strongly and develops a **thermal low** (over north-west India and Pakistan); the cooler Indian Ocean holds high pressure (the **Mascarene High**). Moist air flows from sea to land, the **south-east trades cross the equator**, turn right by **Ferrel's law**, and arrive as the **south-west monsoon**.
- **Winter:** the cold continent carries high pressure; dry air flows from land to sea as the **north-east monsoon**, which rains only where it crosses water (Tamil Nadu, eastern Philippines, western Japan).
- **Criticism:**
  - The **thermal low over north-west India is shallow** (below about 700 hPa) and the winter high **too shallow** to reverse the wind.
  - It cannot explain the sudden burst, the breaks, or the year-to-year swings in rainfall.
  - Land is hottest in May, yet the monsoon sets in during June; the hottest area, the Thar, is among the driest.
  - Onshore winds alone do not make rain: rain needs uplift by mountains, monsoon depressions and convergence. During the strongest monsoon flow, rain is often scarce away from mountain slopes.
- **Current view:** land–sea heating contrast remains a necessary condition, but heating of the whole troposphere over land and the moist energy of the air matter more than surface temperature alone.

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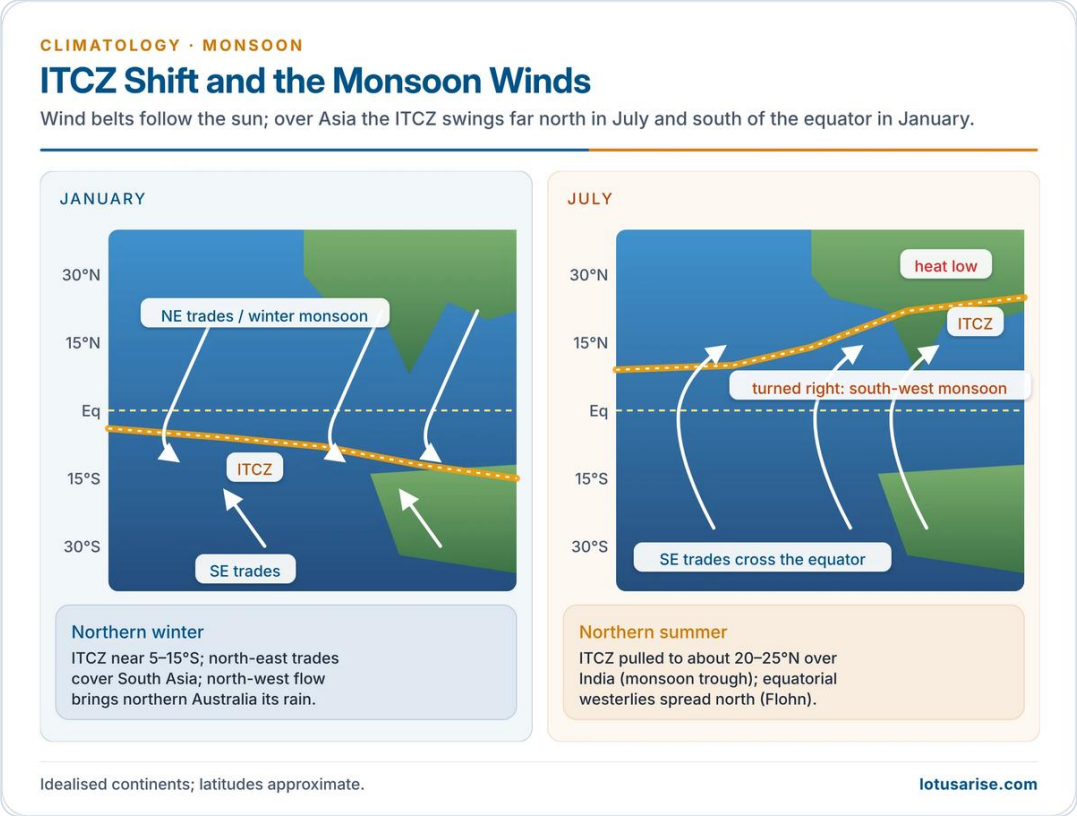
Air-Mass (ITCZ) Theory

- The monsoon is explained by the **seasonal migration of the Inter-Tropical Convergence Zone** and the air masses on either side of it.
- **Summer:** the ITCZ moves to about **20–25°N** over India as the **monsoon trough**, drawing equatorial maritime air from the southern hemisphere across the equator. Rain falls along the convergence and in the disturbances it spawns.
- **Winter:** the ITCZ moves **south of the equator**; India comes under dry continental air and the north-east trades.
- **Criticism:** the monsoon trough is a thermal trough, not a classic meeting of two trade systems, and the theory does not explain the abrupt onset or the upper-air reversal.

Dynamic Concept: Hermann Flohn (1951)

- **Hermann Flohn (1951)** held that the monsoon is simply the **normal seasonal migration of the planetary wind and pressure belts** following the overhead sun, magnified over continents.
  - The mean axis of the **equatorial westerlies** lies near **10°N in July** and **5°S in January**.
  - Regions between two belts fall under opposite regimes in the two seasons.
- **Summer monsoon** = the **equatorial westerlies displaced north**, not a prolonged south-east trade.
- **Winter monsoon** = the **north-east trades re-established**, not an outflow from a thermal high.
- **Continental versus oceanic tropics:** over land, the annual temperature range is large and the belts shift by many degrees (Africa, India–Australia); over the open Pacific they shift only a little, so no monsoon forms there.
- **Criticism:** it neglects the upper-air circulation and the role of the **Tibetan Plateau**, which Flohn himself later stressed, and the "equatorial westerlies" over India are deeper and stronger than a simple shift would give. It remains the framework that the global-monsoon view builds on.

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03 Upper-Air Theories

Jet Stream Theory: Maung Tun Yin (1949) PYQ 2006

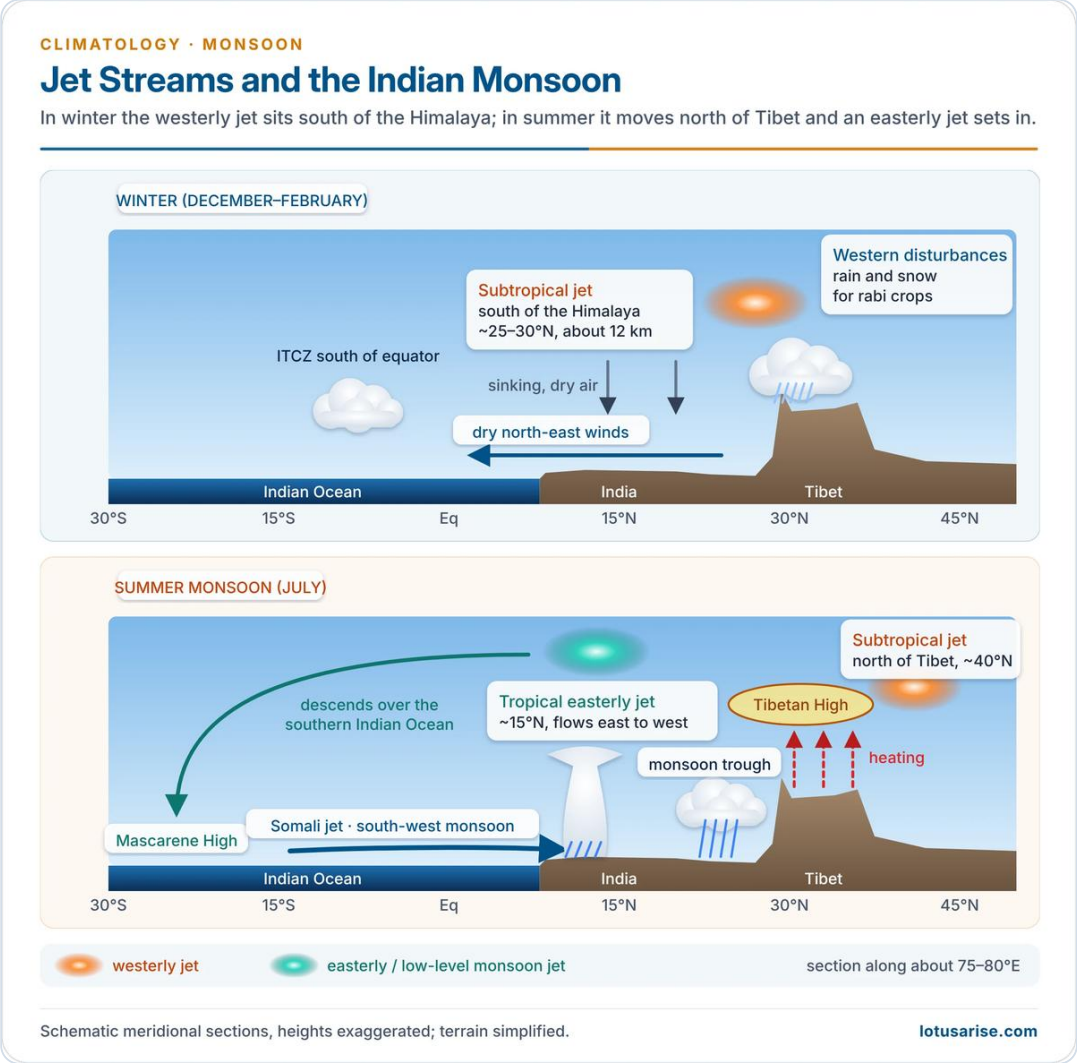
- **Maung Tun Yin (1949)** linked the onset to the **subtropical westerly jet (STJ)**:
  - In winter and spring the STJ blows **south of the Himalaya**; its westerly, subsiding flow blocks the monsoon current.
  - In **early June** the jet leaves the south side of the plateau and re-forms north of Tibet (about **40°N**). The monsoon then bursts over India within days.
  - In **mid-October** the jet returns south of the Himalaya and the monsoon withdraws.
- He saw the **Himalaya–Tibet massif** as a mechanical barrier whose hydrodynamic effect, not the thermal low, times the onset.
- **Criticism:** some observations show the monsoon arriving before the jet's northward jump, and the theory says little about rainfall amount.

Tibetan Plateau as Heat Source: P. Koteswaram (1958)

- **P. Koteswaram (1958)** identified the **tropical easterly jet (TEJ)** and traced it to summer heating of the **Tibetan Plateau**, about **2.5 million km²** at an average height above **4,000 m**.
- **Mechanism:**
  1. In summer the plateau surface heats the air directly at mid-tropospheric height, making it an **elevated heat source**.

2. A **warm-core anticyclone** forms over it in the upper troposphere (about 200–100 hPa): the **Tibetan (South Asian) High**.
3. On its southern flank an **easterly jet** develops near **15°N** at about **100–150 hPa** and extends west to Africa.
4. The TEJ descends over the southern Indian Ocean, strengthening the **Mascarene High**; air from there flows north, crosses the equator as the **Somali jet**, and feeds the **south-west monsoon**.
5. **Latent heat** released by monsoon rain strengthens the upper anticyclone, a positive feedback.

- In **October** the plateau cools, the anticyclone and TEJ collapse, the STJ returns and the monsoon retreats.
- **Field evidence:** the **Indo-Soviet Monsoon Experiment (ISMEX, 1973)** and the international **MONEX (1979)** confirmed the plateau's role and the cross-equatorial low-level jet.
- **Evaluation: William Boos and Zhiming Kuang (2010)** argued from models that the **Himalaya**, by insulating warm, moist tropical air from cold, dry air to the north, matters more than plateau heating. The barrier versus heat-source debate continues.



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Burst, Breaks and the Rain-Makers

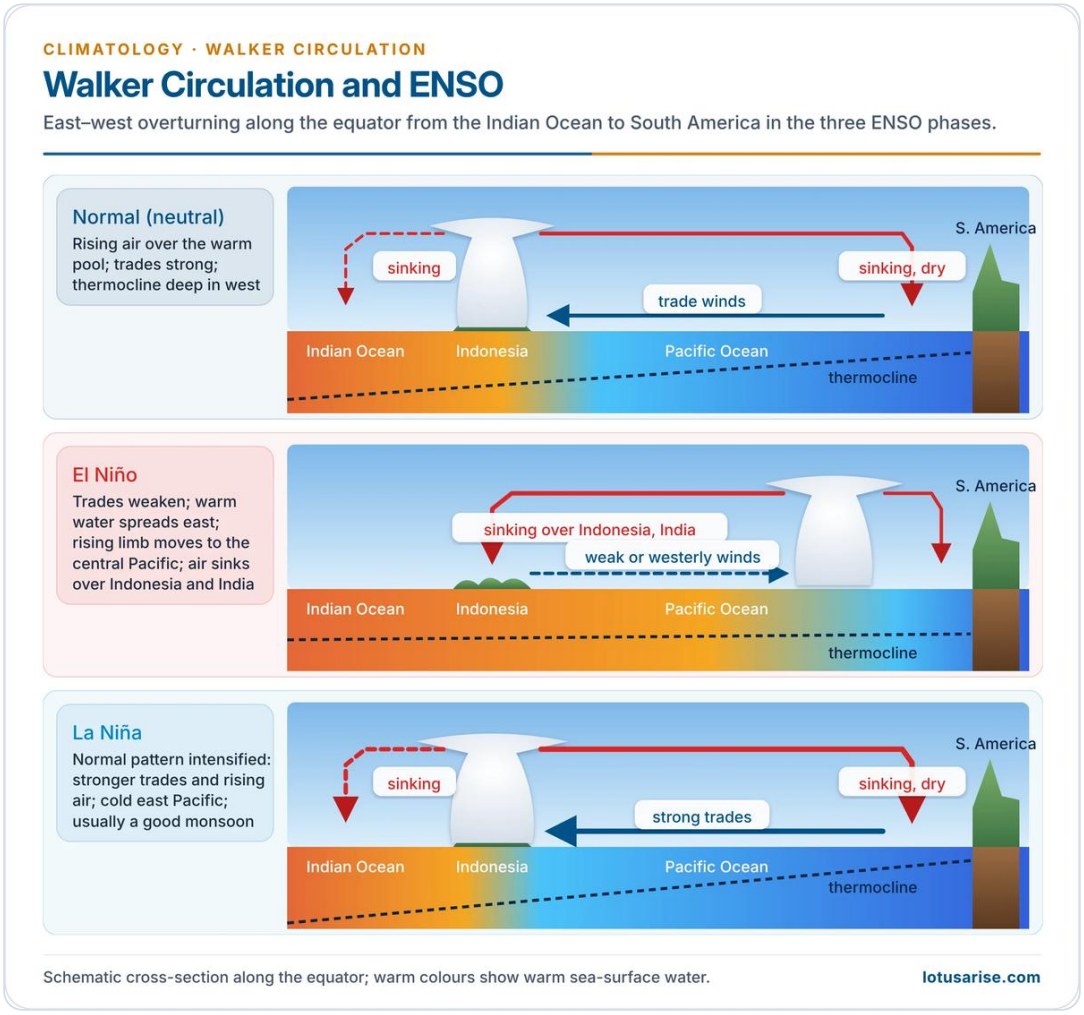
- **Burst:** the onset is abrupt, with thunderstorms, a sharp fall in day temperature and a rise in humidity. Its normal date over **Kerala** is 1 June (about ±7 days); the monsoon covers the whole country by about 8 July.
  - The **2025** monsoon reached Kerala on 24 May, its earliest since 2009; in **2026** it arrived on 4 June.
- **Breaks:** spells of a week or more with little rain over central India, when the monsoon trough shifts to the Himalayan foothills; the foothills and the north-east then get heavy rain.
- **Rain-makers:** the south-west current is a necessary but not sufficient condition. Rain comes from **monsoon depressions and lows** from the Bay of Bengal, the **monsoon trough**, offshore troughs and vortices on the west coast, and orographic uplift.
  - The monsoon's chief role is to fill the lower atmosphere with moisture; the disturbances supply the lift.

04 Teleconnections: Ocean–Atmosphere Theories

El Niño–Southern Oscillation (ENSO)

- **Gilbert Walker**, searching in the 1920s for predictors of the monsoon after the famines of the late nineteenth century, found the **Southern Oscillation**, the see-saw of pressure between the Indian Ocean and the South Pacific.
- **Mechanism:** in an **El Niño**, the rising limb of the **Walker circulation** shifts east into the central Pacific and **air sinks over the Indian region.** This weakens convection, the **Tibetan High** and the **TEJ**, so the monsoon is weaker. **La Niña** generally strengthens it.
- **Evidence: 2002, 2009, 2015** and **2023** were El Niño years with deficient or below-normal monsoons; **August 2023** was India's driest August since 1901. The **2026** monsoon, under a developing El Niño, ended at about 87% of the long-period average, the lowest since 2015.
- **Evaluation:** the link is probabilistic, not fixed.
  - **K. Krishna Kumar, Balaji Rajagopalan and Mark Cane (1999)** found it weakening after the 1980s; the strong El Niño of **1997** brought a near-normal monsoon.
  - **Central-Pacific ("Modoki")** El Niños tend to hurt the monsoon more than eastern ones, and the warming Indian Ocean and the **IOD** modulate the effect. Recent studies disagree on whether warming is weakening or strengthening the link.

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Indian Ocean Dipole (IOD) and EQUINOO

- The **IOD**, described by **N. H. Saji, B. N. Goswami, P. N. Vinayachandran and Toshio Yamagata (1999)**, is the difference in sea-surface temperature between the western Arabian Sea and the eastern Indian Ocean off Sumatra.
  - **Positive IOD:** warm west, cool east; rising air over the western Indian Ocean favours the Indian monsoon and can offset El Niño (**1997**; **2019**, when the monsoon ended at 110% of normal).
  - **Negative IOD:** warm east, cool west; generally unfavourable.
- The **Equatorial Indian Ocean Oscillation (EQUINOO)**, the see-saw of convection between the western and eastern equatorial Indian Ocean, identified by **Sulochana Gadgil** and colleagues (2004), is its atmospheric partner and also helps explain monsoons that defy ENSO.

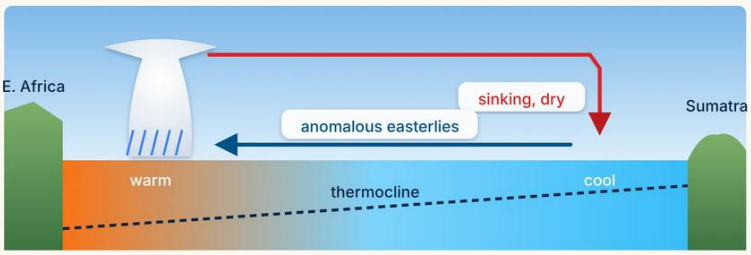
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CLIMATOLOGY · MONSOON

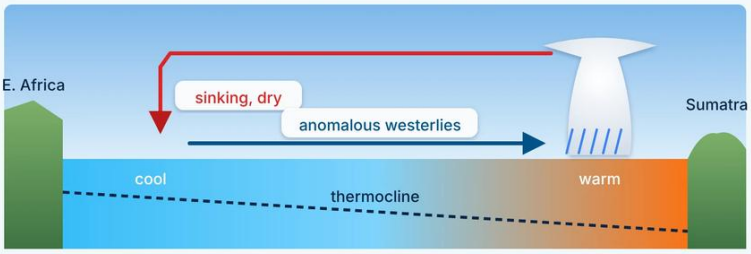
Indian Ocean Dipole

An east–west see-saw of sea-surface temperature and convection across the equatorial Indian Ocean.

Positive IOD
Warm west, cool east; rising air over western Indian Ocean; favours the Indian monsoon (1997, 2019)



Negative IOD
Warm east, cool west; rising air near Sumatra and Australia; usually unfavourable for the Indian monsoon



Schematic cross-section along the equator from East Africa to Sumatra. lotusarise.com

Madden–Julian Oscillation (MJO)

- The **MJO**, found by **Roland Madden and Paul Julian (1971–72)**, is an eastward-moving pulse of tropical convection that circles the globe in about 30–60 days.
- Its northward-moving summer counterpart, the **boreal summer intraseasonal oscillation**, sets the active–break rhythm of the Indian monsoon and can advance or delay the onset.

05 Synthesis and the Changing Monsoon

THEORY	PROPONENT	CORE IDEA	MAIN GAP
Thermal	Edmond Halley (1686)	Seasonal land–sea pressure contrast	Burst, breaks, variability
Air-mass / ITCZ	—	Seasonal ITCZ migration draws equatorial air	Upper air; abrupt onset
Dynamic	Hermann Flohn (1951)	Shift of planetary belts; equatorial westerlies	Upper air; Tibet
Jet stream	Maung Tun Yin (1949)	STJ jumps north of Tibet, releasing monsoon	Rainfall amount; timing debated

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THEORY	PROPONENT	CORE IDEA	MAIN GAP
Tibetan heat source	P. Koteswaram (1958)	Tibetan High, TEJ, Mascarene High chain	Barrier versus heating debate
Teleconnections	Gilbert Walker; later work	ENSO, IOD, MJO modulate strength and timing	Links shift over decades

- **Present understanding:** the monsoon is a coupled land–ocean–atmosphere system. Its existence comes from the **seasonal migration of the tropical rain belt** over a large continent, its form from the **Himalaya–Tibet massif**, its rain from synoptic disturbances, and its year-to-year swings from ENSO, IOD and intraseasonal oscillations.
- **Monsoon and warming:**
  - The **IPCC (2021)** attributes the **decline of South Asian monsoon rain in the second half of the twentieth century** mainly to aerosols, and projects monsoon rainfall to increase over South Asia in the long term as greenhouse warming dominates.
  - **Roxy Mathew Koll** and colleagues (2017) found a threefold rise in widespread extreme rain events over central India between 1950 and 2015, even as moderate rain declined: fewer rainy days, heavier bursts.

Previous Year Questions

2026	Define ‘pseudo monsoon’ and explain its spatial distribution.
2026	The relationship between El Niño and the Indian monsoon is becoming complex under the conditions of global warming. Critically examine.
2020	Explain how various factors influence the origin and development of the Indian monsoon system.
2014	Discuss the nature and origin of Indian monsoon and recent techniques of its prediction.
2013	Discuss the mechanism of Indian Monsoon.
2008	Discuss the mechanism and origin of Monsoon winds & explain the role of El Nino on Monsoon circulation.

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2006	Give a critical account of the recent theories of origin of Indian monsoon with special reference to Jet Stream Theory.
2002	Explain the origin, mechanism and characteristics of Summer Monsoon in India.
1999	Elucidate the mechanism of the Indian Monsoon.
1994	Discuss the recent theories put forward to explain the origin and mechanism of the Indian Monsoon.

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5 chapters · from page 6

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8 chapters · from page 55

03 **Moisture, Stability and Precipitation**
5 chapters · from page 133

04 **Air Masses, Fronts and Storms**
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