

SCIENCE COURSE

Weather & Meteorology Fundamentals

8 Chapters

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WEATHER & METEOROLOGY FUNDAMENTALS

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Weather & Meteorology Fundamentals

Course 1 · Chapter 1 · Why Study Weather? Scope & Sources

On the evening of 15 October 1987, a British television forecaster is remembered for telling viewers not to worry because there was no hurricane on the way. The next night, a storm of unusual violence crossed southern England and killed people, brought down millions of trees and became known as the Great Storm. The forecaster's words have been quoted ever since as an example of a forecast gone wrong. The truth is more interesting, and it makes a good first lesson: he was in fact answering a question about a hurricane in another part of the world, the storm that hit Britain was not technically a hurricane, and the models of the day had given only a weak warning (check all of this before repeating it). This chapter explains why weather is worth studying, sets out what the course covers, and shows how to tell weather facts from weather folklore.

Weather and Climate

People use the two words loosely, so it helps to fix them early.

Weather

What the atmosphere is doing at a place and time: today's rain, this afternoon's wind, tomorrow's frost. It changes by the hour.

Climate

The pattern of weather over a long period, usually thirty years or more (check the convention): the typical winters, the average rainfall, the range of extremes.

Why it matters

A cold week does not disprove a warming climate, and a hot day does not prove one. Weather is the individual game; climate is the season's record.

The Five Things to Watch

A huge amount of weather can be described with a handful of measurements.

Variable	What it is	How it is measured
Temperature	How warm or cold the air is	Thermometer, kept in the shade and ventilated
Pressure	The weight of the air above a point	Barometer; reported in millibars or hectopascals
Humidity	How much water vapour the air holds	Hygrometer; often given as relative humidity or dew point
Wind	Air moving from one place to another	Anemometer for speed, vane for direction
Precipitation and cloud	Water falling or hanging in the sky	Rain gauge, observers, satellites and radar

Much of the course is about how these five variables interact. Warm air rises, which lowers pressure; moist air cools as it rises and forms cloud; pressure differences drive the wind; and the wind carries moisture and heat from place to place.

How Can Weather Be Forecast at All?

The atmosphere is a fluid obeying the laws of physics, and so in principle its future can be calculated from its present. The English scientist Lewis Fry Richardson tried this by hand around the time of the First World War, and his attempt was a failure in practice but a success as an idea (check the date and the details). Electronic computers made the idea practical: the first successful computer weather forecast was produced around 1950 (check). Since then, forecasting has become a global effort in which observations from weather stations, balloons, ships, aircraft and satellites are fed into computer models (Chapter 7).

Why forecasts have limits

In the early 1960s the meteorologist Edward Lorenz found that tiny differences in the starting numbers of a simple weather model led to completely different results after a while (check the details). The finding is the basis of the idea of chaos, often illustrated by the image of a butterfly's wings changing the weather weeks later. The practical conclusion is that there is a limit, of roughly one to two weeks for detailed day-by-day

forecasts, beyond which no model can see (check the figure). Forecasts have improved steadily, but they cannot be perfect.

What the Course Covers

Chapters	Theme
2–3	The atmosphere; heat, moisture and clouds
4–5	Wind and pressure; fronts and depressions
6–7	Storms and extremes; how forecasts are made
8	Weather, climate and change

What the course leaves out

This is an introduction for the curious, not a training for forecasters. It uses plain language and ideas, with the minimum of mathematics, and it leans on examples from the British Isles. It does not cover climate science in depth, ocean science or the technology of instruments beyond what the story needs.

Record, Folklore and Memory

The Great Storm story shows why this distinction matters. Three kinds of claim need different handling.

Record

Measured values: a pressure reading, a rainfall total, a wind gust, found in observing records and official reports.

Folklore

Sayings such as "red sky at night, shepherd's delight". Some have a basis: in mid-latitudes weather systems usually move from the west, so a red sunset can mean clear air to the west (check). Others are plain wrong, and none is a forecast.

Memory

What people recall of a famous storm or a hard winter. Good for mood, unreliable for dates and figures: the heat of a summer or the depth of a snowfall is nearly always remembered as greater than the records say.

A note on accuracy

Dates, names and figures in this course are given from general knowledge and checked as each chapter is written. Where a point is uncertain the text says so. Before quoting a record temperature or a storm's toll elsewhere, check it against an official source such as a national weather service.

Where to Get Data and Read More

- **Your national weather service.** The UK Met Office publishes forecasts, charts, warnings and historical records for free. Other countries have equivalents.
- **Surface pressure charts.** Analysis charts with lines of equal pressure (isobars) and fronts are published daily and are the best practice for the later chapters.
- **Satellite and radar images.** Many weather services and agencies publish near-real-time images of cloud and rain.
- **Climate records.** National weather services and international bodies hold long series of temperature and rainfall (check what is available for your area).
- **A home record.** A cheap thermometer and a rain gauge in the garden, and a notebook, make the course concrete.

Exercises

EXERCISE 1

In three sentences, explain the difference between weather and climate, and give one example of a mistake people make by confusing them.

→ Solution

EXERCISE 2

Sort these into record, folklore or memory: (a) the pressure at a weather station fell by 20 millibars in a day; (b) "red sky at night, shepherd's delight"; (c) your recollection of the hottest day you can remember.

→ Solution

EXERCISE 3

For one week, note each morning and evening the five variables where you can (temperature, pressure, humidity, wind, cloud or rain), using a forecast service or your own instruments, and write two sentences on what changed and what did not.

→ Solution

Quick Reference

- **Weather versus climate:** what the air is doing now versus the long-term pattern
- **Five variables:** temperature, pressure, humidity, wind, precipitation and cloud
- **Forecasting:** physics plus observations plus computer models
- **Limits:** chaos (Lorenz); detailed forecasts fade after one to two weeks
- **Handling sources:** separate record, folklore and memory
- **First stops:** the national weather service, pressure charts, satellite and radar
- **Check:** the Great Storm details, dates, the figures for forecast limits

Next chapter: The Atmosphere, which covers its layers, its composition and why weather lives in the lowest of them.

Weather & Meteorology Fundamentals

Course 1 · Chapter 2 · The Atmosphere

Everything in this course happens in a thin shell of gas around a rock. If the Earth were the size of an apple, the part of the atmosphere in which nearly all weather occurs would be thinner than the apple's skin (check the comparison, which is a common illustration and depends on how the layer is defined). Before looking at clouds, wind and storms, it helps to know what the air is made of, how it is arranged in layers and why it is the lowest layer that matters. Figures are given from general knowledge and flagged where they should be checked.

What the Air Is Made Of

Gas	Share of dry air	Note
Nitrogen	About 78 per cent	Mostly inert in everyday weather
Oxygen	About 21 per cent	What animals breathe
Argon	About 0.9 per cent	An inert gas
Carbon dioxide	About 0.04 per cent	A small share, but important for heat balance (check the current value)
Water vapour	Roughly 0 to 4 per cent	Highly variable; the fuel of clouds and rain

The bulk gases make little difference to day-to-day weather. The interesting actors are the smallest and most variable: water vapour above all, and the tiny particles of dust, salt and smoke around which cloud droplets form (Chapter 3).

Layers

The atmosphere is divided into layers according to how its temperature changes with height. The boundaries are approximate and vary with latitude and season.

Troposphere

Stratosphere

From the ground to roughly 8 to 18 kilometres, higher at the equator than at the poles (check). Temperature falls with height. It holds most of the air and nearly all the water vapour, and it is where weather happens.

Above the tropopause, up to about 50 kilometres. Temperature rises with height because the ozone layer absorbs ultraviolet light (check). Airliners fly in its lower edge, and storm tops flatten against its base.

Mesosphere

Up to about 85 kilometres, where temperature falls again. Meteors burn up here.

Thermosphere and beyond

Very thin air that is heated by the sun's most energetic radiation. Auroras occur here, and satellites orbit within it or beyond. The edge of space is conventionally placed around 100 kilometres (check).

The ceiling of weather

The tropopause, the boundary between the troposphere and the stratosphere, acts like a lid. A towering thundercloud rises until it reaches this layer, where the air stops cooling with height, and then spreads out sideways in the familiar anvil shape. You can see the lid, on a summer day, in the flat top of a big storm cloud.

Pressure and Height

Air has weight, and the pressure at any point is the weight of the column of air above it. At sea level the standard value is about 1013 hectopascals (the same as millibars, check). Pressure falls quickly with height at first and more slowly later, roughly halving for every 5 to 6 kilometres climbed (check). Half of the atmosphere's mass therefore lies below about that height, and on the summit of Mount Everest the pressure is about a third of the sea-level value (check).

Why pressure is the weather's best clue

Pressure at a place changes as masses of air of different density move over it. Falling pressure usually means an approaching system and more unsettled weather, and rising pressure means settling conditions (check the rule, which is a rough guide only). That is

why barometers have long hung in hallways and on ships, and why pressure charts are the working map of the forecaster.

Temperature with Height

In the troposphere, air cools as it rises, by an average of about 6.5 degrees Celsius per kilometre in the standard atmosphere (check). That is why mountains are cold and snow lies on their tops even in summer. The rate varies with moisture and conditions, and the way in which it varies decides whether rising air continues to rise or sinks back, which is the central question in Chapter 3.

Measuring the Air: A Short History

- **The barometer.** The Italian physicist Evangelista Torricelli made the first mercury barometer in the 1640s (check). It showed that air has weight.
- **A French experiment.** In 1648 a barometer was carried up a mountain in central France, the Puy de Dôme, at the request of Blaise Pascal, and the mercury fell as the party climbed, confirming that pressure drops with height (check the details and who carried out the climb).
- **A Scottish observatory.** An observatory on the summit of Ben Nevis, Britain's highest mountain, recorded the weather every hour for two decades from the 1880s and produced a valuable record of conditions at altitude (check the dates).
- **Balloons and radiosondes.** Instrumented balloons, released twice a day around the world, now send back temperature, pressure, humidity and wind from the whole depth of the troposphere (Chapter 7).

Check the details

The heights of the layers, the sea-level pressure and the lapse rate are all averages from a standard model, and real values differ from day to day and place to place. Confirm figures against an official source before using them in calculations.

Exercises

EXERCISE 1

Name the four lowest layers of the atmosphere in order, and say how temperature changes with height in each.

→ Solution

EXERCISE 2

Using a lapse rate of 6.5 degrees per kilometre, estimate the temperature at the top of a 1,300-metre mountain if the valley is at 12 degrees, and say why a real figure might differ.

→ Solution

EXERCISE 3

Explain why nearly all weather occurs in the troposphere, and what the tropopause does to a growing thundercloud.

→ Solution

Quick Reference

- **Air:** about 78 per cent nitrogen, 21 per cent oxygen, plus argon, carbon dioxide and variable water vapour
- **Layers:** troposphere, stratosphere, mesosphere, thermosphere
- **Troposphere:** about 8 to 18 km deep; temperature falls with height; holds the weather
- **Tropopause:** the lid that flattens storm tops into anvils
- **Pressure:** about 1013 hPa at sea level; roughly halves every 5 to 6 km
- **Lapse rate:** about 6.5 degrees C per km on average
- **Check:** layer heights, standard values, historical dates

Next chapter: Heat, Moisture and Clouds, which covers how the sun's energy and water vapour make clouds.

Weather & Meteorology Fundamentals

Course 1 · Chapter 3 · Heat, Moisture and Clouds

Every cloud is a story in three steps: the sun supplies energy, water is lifted into the air, and the air cools until the water becomes visible. This chapter follows those steps. It explains where the heat comes from, how air holds moisture, why rising air cools and what happens when it cools enough, and how the resulting clouds are classified. By the end you should be able to look at a sky and say something sensible about what the air is doing. Figures are given from general knowledge and flagged where they should be checked.

Where the Heat Comes From

Almost all the energy that drives weather comes from the sun. About thirty per cent of the sunlight reaching the Earth is reflected straight back to space by clouds, air and bright surfaces such as ice (check the figure). The rest is absorbed, mostly by the land and sea, which warm up and then warm the air above them. The air is heated from below, not from above, which is one reason the lowest layer is the unsettled one (Chapter 2).

Radiation

Energy travelling as light and heat rays, from the sun to the ground and from the ground back out to space.

Conduction

Heat passing directly from a warm surface to the thin layer of air touching it. It is slow, and affects only the lowest metres.

Convection

Warm air rising and cooler air sinking. This is how heat is carried upward and the engine of much weather.

Latent heat

Energy absorbed when water evaporates and released when it condenses. Condensation in a cloud warms the air around it, which can help the cloud grow.

Moisture in the Air

Warm air can hold more water vapour than cold air. Meteorologists use two measures to describe how moist the air is.

Measure	What it tells you	Note
Relative humidity	How full the air is, as a percentage of what it could hold at its current temperature	Changes with temperature even if the water content does not
Dew point	The temperature to which the air would have to cool to become saturated	A better guide to how much moisture is really present

When the air temperature falls to the dew point, the air is saturated, and the vapour begins to condense into liquid droplets. That is why dew forms on grass on a clear night, and why a cold glass of water "sweats" on a warm day.

> **Dew point as a comfort guide**
>
> A dew point near the air temperature means damp, grey or foggy weather is close. A big gap means dry air. In summer, a high dew point is what makes the air feel muggy, even when the temperature is not extreme.

Why Rising Air Cools

When a parcel of air rises, it moves into lower pressure, expands, and cools. No heat needs to leave it: the cooling comes from the expansion alone (check the explanation). Dry air cools at about 10 degrees Celsius per kilometre as it rises (check the figure, usually given as 9.8). Once it is cooled to its dew point, condensation begins, which releases latent heat and slows the cooling, so saturated air cools more slowly, at a rate that varies with temperature (check). This difference decides whether a rising parcel keeps rising: if it stays warmer than its surroundings, it carries on upward and builds a tall cloud.

From Vapour to Cloud to Rain

Water vapour does not condense easily in perfectly clean air. It needs tiny particles, such as salt, dust or smoke, called condensation nuclei, to gather on (check). A cloud is a collection of billions of droplets or ice crystals, each far too small to fall. Rain forms when droplets grow large enough, by colliding and merging, or, in cold clouds, by ice crystals growing at the expense of supercooled water droplets, a process named after the scientist who described it (check the

details). Both routes need time and a thick enough cloud, which is why drizzle falls from thin cloud and heavy rain from thick.

Fog is cloud at the ground

Fog forms when the air near the surface cools to its dew point. On the east coast of Scotland, a cold sea fog that rolls in from the North Sea in spring and summer has its own local name, the haar (check). The same physics that makes a cloud in the sky makes fog on the ground, only the cooling comes from the cold sea or a clear night instead of from rising.

Naming the Clouds

In 1802 an English pharmacist and amateur meteorologist, Luke Howard, proposed a system of Latin names for clouds, which is the basis of the system still used (check the date and details). The main ideas are simple.

Name part	Meaning	Example
Cirro-	High cloud, made mostly of ice crystals	Cirrus: thin wisps
Alto-	Middle-level cloud	Altocumulus: patchy puffs
Cumulus	Heaped, with a flat base	Fair-weather cumulus
Stratus	Layered, sheet-like	Low grey stratus
Nimbo- or -nimbus	Rain-bearing	Nimbostratus, cumulonimbus

Check the details

Typical heights of cloud levels, the dry and saturated cooling rates and the share of sunlight reflected all vary with place and season. Confirm figures against an official source, such as a national weather service's cloud guide, before using them in calculations.

Exercises

EXERCISE 1

Explain why air is mostly heated from below, and name the four ways heat moves in the atmosphere, with a one-line example of each.

→ Solution

EXERCISE 2

Air at 15 degrees Celsius has a dew point of 5 degrees. Using a cooling rate of 10 degrees per kilometre for rising dry air, estimate the height at which cloud would begin to form, and say what assumption you made.

→ Solution

EXERCISE 3

Look at the sky on three different days and name the cloud type or types you see, using the table, saying which weather each suggests.

→ Solution

Quick Reference

- **Energy:** from the sun; about a third reflected; the rest warms land and sea first
- **Heat transfer:** radiation, conduction, convection, latent heat
- **Moisture:** relative humidity and dew point
- **Rising air cools:** about 10 degrees per km when dry; slower once saturated
- **Cloud formation:** cooling to the dew point plus condensation nuclei
- **Names:** cirro-, alto-, cumulus, stratus, nimbus
- **Fog:** cloud at the ground

Next chapter: Wind and Pressure, which covers why air moves and how the Earth's spin shapes the flow.

Weather & Meteorology Fundamentals

Course 1 · Chapter 4 · Wind and Pressure

Wind is air moving from where there is more pressure to where there is less. That sentence is the whole of the idea, but the details are what make weather charts readable: the Earth's spin bends the wind, so it circles around highs and lows instead of rushing straight between them, and on the largest scale the same ideas arrange the winds of the planet into belts. This chapter explains the forces at work, shows how to read wind from a pressure chart and describes the great circulation. Figures are given from general knowledge and flagged where they should be checked.

The Push from Pressure

Where air is heated, it expands and rises, leaving lower pressure at the surface; where air cools and sinks, pressure at the surface is higher. The difference in pressure between two places creates a force that pushes air from high toward low, called the pressure gradient force. On a chart, pressure is drawn as lines of equal value, called isobars, and the closer together they are, the steeper the gradient and the stronger the wind.

> **Reading the chart**
>
> Tightly packed isobars mean strong wind, widely spaced isobars mean light wind. You can judge the windiness of a chart at a glance before reading any numbers, in the same way you judge the steepness of a hill from the crowding of contour lines on a map.

The Spin of the Earth

Air does not flow straight from high to low pressure, because the Earth rotates beneath it. Seen from the ground, moving air appears to be pushed sideways: to the right in the Northern Hemisphere and to the left in the Southern. This apparent deflection is called the Coriolis effect, after the French engineer and mathematician Gaspard-Gustave Coriolis, who described it in the 1830s (check the date and the details). It is zero at the equator and strongest at the poles, and it matters for large, slow movements such as weather systems, not for a bath plug or a small stream (check this common misconception).

Low pressure

In the Northern Hemisphere, air circulates anticlockwise around a low and spirals slightly inward. Air converges, rises, and cloud and rain are common.

High pressure

In the Northern Hemisphere, air circulates clockwise around a high and spirals slightly outward. Air sinks, and the weather is usually settled and dry.

Buys Ballot's rule

Stand with your back to the wind in the Northern Hemisphere, and low pressure is to your left (check the name and date: a Dutch meteorologist, in the 1850s). It is a quick way to locate a low.

Friction

Near the ground, friction slows the wind and lets it cross the isobars toward low pressure at an angle. Higher up, the wind runs nearly along the isobars.

The Great Circulation

On a planetary scale, the sun heats the equator more than the poles, and the atmosphere carries heat toward the poles. The Earth's spin splits this flow into belts, in each hemisphere.

Belt	Latitude (roughly)	Character
Trade winds	0 to 30 degrees	Steady winds blowing toward the equator, from the east
Subtropical highs	About 30 degrees	Sinking air, dry weather; many deserts lie here
Westerlies	30 to 60 degrees	Winds from the west; the belt that brings changeable weather to the British Isles
Polar easterlies	60 to 90 degrees	Cold winds from the east near the poles

The pattern is conventionally described as three cells in each hemisphere, named the Hadley, Ferrel and polar cells (check the names and the details, since the Ferrel cell is a simplified idea). Near the equator, the trade winds from the two hemispheres meet in a band of rising air, heavy cloud and heavy rain called the intertropical convergence zone (check).

The jet streams

High in the troposphere, near the tropopause, narrow ribbons of very fast wind blow from west to east, at speeds that can exceed 200 kilometres per hour (check). They lie along the boundaries between warm and cold air and steer the storms of the mid-latitudes. They became widely known during the Second World War, when high-flying bombers found themselves slowed or sped by unexpectedly strong winds (check the history). When a jet stream sits to the north or south of its usual position, the weather in the British Isles changes with it.

Local Winds

On smaller scales, uneven heating creates local winds. The sea breeze is the classic example. By day the land heats faster than the sea, air rises over the land, and a cooler breeze flows in from the sea to replace it. At night the land cools faster, and the flow reverses into a gentler land breeze. Winds in valleys and mountains follow similar logic.

Measuring Wind: The Beaufort Scale

Before instruments were common, the wind was described by its effects. The Beaufort scale, devised by a British naval officer, Francis Beaufort, in the early nineteenth century, ranks wind from 0 (calm) to 12 (hurricane force) according to what it does to smoke, trees and the sea (check the date and the details). A light breeze, force 2, is enough to rustle leaves; a gale, force 8, breaks twigs and makes walking difficult; force 12 is destructive (check the thresholds). Modern forecasts give speeds, but the Beaufort scale is still used in shipping forecasts.

Check the details

Statements about the direction of spin of water in a sink, the number of cells in the circulation and the maximum speeds of the jet streams are often repeated incorrectly. Confirm any figure against an official source before using it.

Exercises

EXERCISE 1

In the Northern Hemisphere, you stand with your back to the wind and note that it is blowing steadily. On which side is the low pressure, and how does the circulation around a low differ from that around a high?

→ Solution

EXERCISE 2

Name the three main wind belts between the equator and the north pole, and say which of them gives the British Isles most of its weather.

→ Solution

EXERCISE 3

Explain why a sea breeze blows from the sea to the land by day, and what you would expect at night.

→ Solution

Quick Reference

- **Wind:** air pushed from high to low pressure; closer isobars mean stronger wind
- **Coriolis effect:** deflects moving air right in the north, left in the south
- **Lows (north):** anticlockwise, converging, rising, cloudy
- **Highs (north):** clockwise, diverging, sinking, settled
- **Belts:** trade winds, subtropical highs, westerlies, polar easterlies
- **Jet streams:** fast ribbons of wind near the tropopause that steer storms
- **Beaufort scale:** 0 (calm) to 12 (hurricane force)

Next chapter: Fronts and Depressions, which covers air masses and the storms of the mid-latitudes.

Weather & Meteorology Fundamentals

Course 1 · Chapter 5 · Fronts and Depressions

Most of the changeable weather in the middle latitudes comes from one pattern: a mass of warm air meeting a mass of cold air along a boundary, with a spinning low-pressure system forming on that boundary. Learn to recognise the air masses, the fronts and the life cycle of the low, and the symbols on a weather chart start to tell a story. This chapter builds on the pressure and wind ideas of Weather & Meteorology Fundamentals 4. Dates and figures are given from general knowledge and flagged where they should be checked.

Air Masses

An air mass is a very large body of air with fairly uniform temperature and moisture, which takes on the character of the region where it forms, called its source region. Air that sits for days over a cold ocean becomes cool and moist; air that sits over a hot desert becomes hot and dry. Air masses are named by their source: polar or tropical for the temperature, and maritime or continental for the moisture.

Air mass	Source	Typical feel in the British Isles
Polar maritime	Cold seas to the north-west	Cool and showery, with good visibility between showers
Tropical maritime	Warm seas to the south-west	Mild, damp and cloudy, with drizzle and hill fog
Polar continental	Northern Europe and Siberia	Very cold and dry in winter, brought by easterly winds
Tropical continental	North Africa and southern Europe	Hot and dry in summer, often hazy
Arctic maritime	Arctic Ocean	Very cold, with snow showers in winter

Why the British Isles are so changeable

The islands sit where several of these air masses compete, with the westerlies (see Weather & Meteorology Fundamentals 4) steering a new one in every few days. A place far inland

on a large continent may sit under one air mass for weeks; Edinburgh rarely does.

Fronts

A front is the boundary between two air masses of different temperature. The term was borrowed from the military language of the First World War by the Norwegian meteorologists who developed the idea, led by Vilhelm Bjerknes and his colleagues in Bergen (check the names, the date and the military link). Fronts are drawn on charts as lines with symbols along them.

Warm front

Warm air advances and rides up over cooler air along a gentle slope. Cloud thickens and lowers over many hours, from high wispy cloud to thick grey layers, with steady rain, then the rain stops and it turns milder. Drawn as a red line with semicircles.

Cold front

Cold air advances and undercuts the warmer air along a steeper slope, pushing it up quickly. The belt of cloud is narrow, with heavy rain or showers, sometimes thunder, then the sky clears and it turns colder and brighter. Drawn as a blue line with triangles.

Occluded front

A cold front moves faster than the warm front ahead of it and catches it up, lifting the warm air off the ground. The weather is a mixture of both fronts. Drawn as a purple line with both symbols.

Stationary front

A boundary that is barely moving, with cloud and rain that can linger for a day or more in the same area.

Reading the sequence

As a typical depression passes over you, the pressure falls and the cloud thickens as the warm front approaches, the weather is mild and damp in the warm sector between the fronts, and then the cold front brings a burst of rain, a veer of the wind and a clear, cooler spell with pressure rising. Falling pressure ahead of the system and rising pressure behind it are the clue to what is coming.

The Life of a Depression

Depression is the traditional British name for a low-pressure system in the mid-latitudes; the word cyclone is also used. Such a low develops along the polar front, the boundary between cold polar air and warm tropical air. The Norwegian model describes a life cycle of several stages (check the details, which have been refined by later research).

1. **A wave forms.** A kink appears on the front, with warm air pushing into the cold on one side and cold air pushing into the warm on the other.
2. **The low deepens.** Pressure at the centre falls, the winds strengthen and circulate anticlockwise, and a warm front and a cold front become distinct, with a warm sector between them.
3. **The cold front catches up.** The cold front moves faster than the warm front and closes the warm sector, forming an occlusion.
4. **The low fills.** With the warm air lifted off the ground, the system loses its source of energy, the centre fills, and the depression decays over a few days.

The jet stream plays a key part. Where it provides divergence aloft, drawing air away from the top of a developing low, the surface pressure falls faster. Rapid deepening of this kind has been called explosive cyclogenesis or, informally, a weather bomb (check the term and the threshold used for it).

Highs, Ridges and Troughs

Between the depressions come calmer spells. A ridge of high pressure, or an anticyclone that settles over the country, gives light winds and clear skies, with fog or frost in winter and heat in summer. In winter, a blocking high that sits in place for days or weeks can divert the Atlantic depressions away and bring prolonged cold or dry spells (check the term and examples). A trough is an elongated area of low pressure, often with a line of showers or a weak front along it.

> **Check the details**
>
> Frontal slopes, speeds and the sequence of cloud are idealised. Real fronts are weaker, stronger or broken up, and the classic textbook model does not fit every depression. Confirm any figure and use the model as a guide, not a rule.

Exercises

EXERCISE 1

A cool, showery north-westerly airstream is replaced by a mild, damp, cloudy south-westerly. Name the air mass in each case and say where each comes from.

→ Solution

EXERCISE 2

Describe the sequence of weather as a depression passes over you, from the first sign of the warm front to the clearance after the cold front, saying what the pressure does at each stage.

→ Solution

EXERCISE 3

Explain how an occluded front forms, and why the depression weakens afterwards.

→ Solution

Quick Reference

- **Air mass:** a large body of air with uniform temperature and moisture, named by source
- **Front:** the boundary between two air masses
- **Warm front:** gentle slope, thickening cloud, steady rain, then milder
- **Cold front:** steep slope, narrow belt of heavy rain, then colder and brighter
- **Occlusion:** the cold front catches the warm front and lifts the warm air
- **Depression:** a mid-latitude low that forms on the polar front and passes through a life cycle

- **Anticyclone:** a high with settled weather; a blocking high can divert the depressions

Next chapter: Storms and Extremes, which covers thunderstorms, tornadoes, hurricanes, snow and ice, and the Great Storm of 1987.

Weather & Meteorology Fundamentals

Course 1 · Chapter 6 · Storms and Extremes

Most weather is ordinary, but a small share of it is violent, and that share causes most of the damage. This chapter looks at the main kinds of severe weather, what energy source drives each, and how the British Isles fit in: far less exposed than some regions, yet far from immune. Dates and figures are given from general knowledge and flagged where they should be checked.

Thunderstorms

A thunderstorm needs three ingredients: moisture near the ground, an unstable atmosphere in which a rising parcel of air stays warmer than its surroundings, and something to start the lift, such as a front, a hill or strong surface heating. The result is a towering cumulonimbus cloud (see Weather & Meteorology Fundamentals 3), which can reach the top of the troposphere.

Lightning

Collisions between ice particles inside the cloud separate electric charge, and the discharge between regions of opposite charge, or between cloud and ground, is lightning (check the details, since the exact charging process is still debated). The flash heats the air to a very high temperature (check), and the sudden expansion is the thunder.

Counting the distance

Light arrives almost instantly and sound takes about three seconds to cover a kilometre (check). Counting the seconds between flash and thunder gives a rough distance to the strike.

Hail

Strong updrafts carry raindrops up into freezing air, where they gather layers of ice and fall only when too heavy to be held up. The stronger the updraft, the larger the stones (check the largest recorded size).

Downbursts

Cold air dragged down by heavy rain can hit the ground and spread outward as a sudden damaging wind, which is why the gust ahead of a storm can be worse than the rain.

Tornadoes

A tornado is a narrow, violently rotating column of air in contact with both the ground and a parent cloud. The strongest form beneath rotating thunderstorms called supercells, and the central United States sees more than anywhere else, in the region nicknamed Tornado Alley (check). The damage is classed on the Fujita scale or its enhanced version, from 0 to 5, according to the destruction caused (check the scale and its origin). The British Isles gets tornadoes too, mostly weak ones, and they are often among the highest per area in the world though not the strongest (check this claim).

> **Waterspouts and funnels**
>
> A funnel cloud is a rotating cone that has not reached the ground. A waterspout is a tornado over water. Neither should be mistaken for the dust devil, a harmless-looking column of whirling dust that forms on a hot, clear day under no storm cloud at all.

Tropical Cyclones

A tropical cyclone is a huge rotating storm that feeds on warm ocean water. It forms over seas warmer than about 26 or 27 degrees Celsius (check the threshold), away from the equator so that the Coriolis effect (see Weather & Meteorology Fundamentals 4) can set it spinning, and it dies quickly over land or cold water. The same storm is called a hurricane in the Atlantic and north-east Pacific, a typhoon in the north-west Pacific and a cyclone in the Indian Ocean and around Australia.

- **Structure:** a calm, clear eye at the centre, surrounded by the eyewall, the ring of the fiercest wind and rain.
- **Scale:** Atlantic hurricanes are rated on the Saffir-Simpson scale from category 1 to 5 by wind speed (check the scale and its thresholds).
- **Storm surge:** the rise of sea level pushed ashore by wind and low pressure is often the deadliest part, and more dangerous than the wind itself.
- **Reaching Europe:** remnants of Atlantic hurricanes sometimes arrive as deep depressions, no longer tropical, and can strengthen the autumn storms of north-western Europe (check examples).

Snow, Ice and Cold

Snow falls when the whole column of air is cold enough, or nearly so, that ice crystals do not melt on the way down. In the British Isles the margin is thin, so a small change in temperature turns snow into rain or sleet. Freezing rain falls as liquid and freezes on contact with cold surfaces, making glaze ice, which is far more dangerous than snow. Cold spells in Britain usually come when a blocking high (see Weather & Meteorology Fundamentals 5) draws air from the east or north.

The Great Storm of 1987

In the early hours of 16 October 1987, a rapidly deepening depression crossed the south of England and the English Channel, bringing the strongest winds in the south-east for many years and felling an estimated fifteen million trees (check the date, the figures and the death toll). It was memorable partly because the forecasts had underestimated the danger, and a widely retold story about a television forecaster's earlier remarks is often misreported (check the story before repeating it). The event led to improvements in forecasting and warnings, and to a greater use of the colour-coded warning system that followed in later years (check the details).

Extremes and Records

Records are exciting but need care, since they depend on the instrument, the site and the rules for accepting a measurement. The highest and lowest temperatures, the strongest gusts and the heaviest rainfall for a place are kept by national weather services and by the World Meteorological Organization, which checks the world records (check the current holders before quoting any figure).

Check the details

Death tolls, damage costs, wind speeds and record values vary between sources and are often revised. Treat every figure in this chapter as approximate and confirm it before quoting it.

Exercises

EXERCISE 1

List the three ingredients a thunderstorm needs, and say how you could estimate how far away a lightning strike was.

→ Solution

EXERCISE 2

Explain why a tropical cyclone weakens quickly when it moves over land, and why the storm surge can be more dangerous than the wind.

→ Solution

EXERCISE 3

Say why a small change in temperature can turn British snow into rain, and why freezing rain is often more dangerous than snow.

→ Solution

Quick Reference

- **Thunderstorm:** moisture, instability and a trigger for lift; cumulonimbus cloud
- **Thunder distance:** about three seconds per kilometre between flash and bang
- **Tornado:** a rotating column in contact with the ground, rated 0 to 5
- **Tropical cyclone:** fed by warm sea; weakens over land; storm surge is the main killer
- **Snow:** needs cold air through the whole column; freezing rain makes glaze ice
- **Great Storm:** 16 October 1987, a rapidly deepening depression over southern England

Next chapter: Forecasting, which covers observation networks, satellites, computer models and ensembles.

Weather & Meteorology Fundamentals

Course 1 · Chapter 7 · Forecasting

A modern forecast is the end of a long chain: millions of measurements, a computer simulation of the atmosphere, many repeated runs to estimate the uncertainty, and a human forecaster who turns the output into something useful. This chapter follows that chain, and ends with how to read a forecast sensibly. It builds on the idea in Weather & Meteorology Fundamentals 1 that a forecast is possible, but limited. Dates and figures are given from general knowledge and flagged where they should be checked.

Observing the Atmosphere

A forecast can be no better than its starting point, so the first job is to measure the present state of the atmosphere as completely as possible.

Source	What it measures
Surface stations	Temperature, pressure, humidity, wind and rainfall at the ground, including automatic stations in remote places
Weather balloons	Radiosondes carried aloft twice a day from sites around the world, reporting temperature, humidity, pressure and wind up through the atmosphere (check the schedule)
Ships and buoys	Conditions over the oceans, which cover most of the planet
Aircraft	Wind and temperature at cruising height, sent automatically by airliners (check)
Weather radar	Where rain, snow and hail are falling, and how it is moving
Satellites	Cloud, temperature and moisture profiles, sea temperature and winds over the oceans

> **Two kinds of satellite**
>
> Geostationary satellites sit high above one spot on the equator and watch the same disc of the Earth continuously, which is how the moving cloud pictures on the news are made.

Polar-orbiting satellites pass much lower over the poles, scanning a new strip of the planet on each orbit and giving more detailed profiles (check the heights). The first weather satellite, TIROS-1, was launched in 1960 (check the date).

Numerical Weather Prediction

The atmosphere obeys the laws of physics: the movement of fluids, the conservation of energy and mass, and the behaviour of gases and water. Numerical weather prediction divides the atmosphere into a three-dimensional grid of boxes and steps the equations forward in time, box by box, from the measured starting state. The idea was set out by the Norwegian Vilhelm Bjerknes in 1904 and attempted by the British mathematician Lewis Fry Richardson, who calculated one forecast by hand during the First World War, with poor results; he imagined a huge hall of human calculators doing it in real time (check the names, the dates and the details).

The first successful computer forecasts came around 1950, and the method has improved steadily since as computers have grown faster and observations more plentiful (check the date). Roughly, forecasts today are as good at five days ahead as they once were at two or three, though this rule of thumb varies by place and season (check).

Why the grid size matters

A model can show only features larger than a few of its grid boxes. A depression is easy to represent; a single thunderstorm or a sea breeze is not, and these are handled by simplified rules called parametrisations. Finer grids resolve more but need vastly more computing power, which is why detailed local models cover only a region and run for a short period ahead.

Chaos, Ensembles and Uncertainty

As Weather & Meteorology Fundamentals 1 explained, tiny errors in the starting state grow until the forecast loses all value, which limits useful detail to roughly one or two weeks (check the figure). To measure the uncertainty, forecasters run the model many times from slightly different starting states, a set called an ensemble. If the runs agree, confidence is high; if they scatter, the forecast is uncertain and the true outcome could be any of several.

- **Probability of precipitation:** a forecast of a 40 per cent chance of rain is usually a statement about the chance of rain at a given place in the period, and it does not describe how much of the area gets wet (check the definition used by your own forecaster).
- **Confidence:** some forecasters give a statement of how sure they are, based on the spread of the ensemble.
- **Persistence and climatology:** the simplest forecasts, that tomorrow will be like today, or like the average for the date, are the benchmark any real forecast has to beat.

The Human Forecaster

The models are not the end of the matter. A forecaster compares several models, spots where each is known to go wrong, interprets local effects such as hills and coasts, and decides on the wording and the warnings. National services such as the Met Office in the United Kingdom issue warnings graded by likelihood and impact (check the current system), and a good forecast communicates risk and not only the most likely outcome.

> **Check the details**
>
> Statements about accuracy, such as how many days ahead forecasts are reliable, depend on the measure used and change as models improve. Dates and attributions in the history of forecasting should also be confirmed against a source.

Reading a Forecast

1. **Look at the date range.** Detail is trustworthy for a day or two, the broad pattern for several days, and little beyond that.
2. **Read probabilities as probabilities.** A 20 per cent chance of rain means that it will often stay dry, but not always.
3. **Check the source.** A national service and a model-based app may disagree; neither is certain.
4. **Watch the trend.** If successive forecasts keep changing, the situation is uncertain; if they stay the same, confidence is higher.
5. **Take warnings seriously.** A warning is about impact, so look at the area, the time and the level.

Exercises

EXERCISE 1

Name four sources of observations used to start a forecast, and say what the main difference is between a geostationary and a polar-orbiting satellite.

→ Solution

EXERCISE 2

Explain in your own words what numerical weather prediction does, and why a model with a coarse grid cannot represent a single thunderstorm.

→ Solution

EXERCISE 3

What is an ensemble forecast, and what does it tell you if the runs all give much the same answer, compared with when they scatter widely?

→ Solution

Quick Reference

- **Observations:** surface stations, balloons, ships, aircraft, radar, satellites
- **Geostationary satellite:** fixed over one spot, continuous view; **polar-orbiting:** lower, scans strips
- **Numerical prediction:** physics equations stepped forward on a three-dimensional grid
- **Parametrisation:** simplified rules for features smaller than the grid
- **Ensemble:** many runs from slightly different starts; the spread shows the uncertainty

- **Reading a forecast:** trust near-term detail, treat probabilities as probabilities, watch the trend

Next chapter: the capstone, Weather, Climate and Change, which joins everything together and looks at how to read claims about the climate.

Weather & Meteorology Fundamentals

Course 1 · Chapter 8 · Weather, Climate and Change

The first chapter of this course drew a line between weather, what the atmosphere is doing now, and climate, the pattern of weather over decades. This final chapter returns to that line and uses everything since: the layers, the heat and moisture, the winds, the fronts and storms, and the limits of forecasting. The aim is not to settle arguments but to give you the tools to read claims about the climate with a clear head. Dates and figures are given from general knowledge and flagged where they should be checked.

Weather Versus Climate, Again

Climate is usually defined as the average and the variability of weather over a period of thirty years or more (check the standard period used by the World Meteorological Organization). A cold week says very little about the climate, in the same way that one hand of cards says little about the deck. A useful saying is that climate is what you expect and weather is what you get.

> **Why the distinction matters**
>
> The limit on forecasting described in Weather & Meteorology Fundamentals 7 applies to the weather on a particular day, not to the average. Even though no one can say whether it will rain in Edinburgh on a particular date next year, it is much easier to say that winters will be wetter than summers, or that the average temperature has shifted. Predicting a distribution is a different, and easier, problem than predicting a single value.

The Energy Balance

Everything in this course runs on energy from the sun (see Weather & Meteorology Fundamentals 3). Over time, the Earth must send back out as much energy as it takes in, or it warms or cools. Incoming sunlight is largely shortwave radiation; the Earth emits longwave, infrared radiation. Some gases in the atmosphere, notably water vapour, carbon dioxide and methane, absorb infrared and re-emit it in all directions, including back down. This is the greenhouse effect, and it is not a controversial idea in itself: without it, the average surface

temperature would be well below freezing (check the figures, usually quoted at around 33 degrees Celsius difference).

- **Natural greenhouse effect:** keeps the planet habitable.
- **Enhanced greenhouse effect:** extra greenhouse gases from human activity, mainly burning fossil fuels and clearing forests, trap more heat. The idea that more carbon dioxide would warm the planet was set out in the nineteenth century, associated with scientists such as Svante Arrhenius (check the names and dates).
- **Feedbacks:** a warmer atmosphere holds more water vapour, which amplifies the warming; melting ice exposes darker surfaces that absorb more sunlight. Clouds are harder, since they can cool or warm depending on type and height (check).

What the Records Show

Climate scientists build the record from thermometers on land and sea, balloons and satellites, and for the more distant past from indirect evidence called proxies, such as tree rings, ice cores, corals and sediments. Several independent groups produce global temperature series and find broadly the same result: the global average has risen since the late nineteenth century, by a little over one degree Celsius, and the last decade is the warmest in the instrumental record (check the figures against a current source from the World Meteorological Organization, NASA, NOAA, the Met Office or Copernicus).

Indicator	What is observed	Where to check
Global temperature	Rising since the late nineteenth century	National and international temperature series
Sea level	Rising, from warming water and melting land ice	Tide gauges and satellite altimetry
Ice	Arctic sea ice and most glaciers shrinking	Satellite records, glacier surveys
Carbon dioxide	Concentration well above the range of the past several hundred thousand years	Direct measurement at Mauna Loa from 1958, and ice cores (check)
Extremes	More frequent heat extremes; changes in heavy rain in many regions	National services, the IPCC reports (check)

Natural variability

Climate has always changed, through variations in the Earth's orbit, the sun's output, volcanic eruptions and ocean cycles such as El Niño and La Niña (check). These natural factors matter for year-to-year swings, and the scientific work of attribution is to separate them from the human contribution. The instrumental record is a few lifetimes long, so claims about the long past rest on proxies and on physical reasoning.

The British Isles in a Changing Climate

For a reader in Scotland, the practical questions are local: warmer and wetter winters, heavier downpours, rising sea level on the coast, and changes in the frequency of the extremes covered in Weather & Meteorology Fundamentals 6 (check the projections from the UK Climate Projections and the Met Office). Attributing any single storm to climate change is harder than attributing a trend, which is why scientists speak of changed odds and not of causes of one event.

How to Read a Claim

1. **Weather or climate?** A single cold snap or hot day is weather; a trend over decades is climate.
2. **Global or local?** A cold winter in one region can sit alongside a warm year for the planet.
3. **Which period and baseline?** A graph that starts at a peak or a trough can say almost anything. Ask what period it covers and what it is compared with.
4. **What is the source?** Prefer national weather services, the IPCC assessments and published studies over social media posts and unsourced charts (check the current reports).
5. **Is the uncertainty stated?** A good claim says how sure it is. Be wary of both certainty about everything and doubt about everything.
6. **Does it fit the physics?** Everything here rests on the same ideas as the rest of the course: energy in and out, water, air in motion.

Check the details

This chapter is a short introduction. Figures for temperature rise, sea level, concentrations and projections change as new data arrive, and the policy questions around the subject

are beyond a fundamentals course. Confirm any number against a current source before using it.

Exercises

EXERCISE 1

A friend says that a cold week in January proves the climate is not warming. Write a short reply using the difference between weather and climate.

→ Solution

EXERCISE 2

Explain the greenhouse effect in a few sentences, and say why it is both natural and capable of being enhanced.

→ Solution

EXERCISE 3

You are shown a chart that appears to prove that temperatures are falling. List four questions you would ask about it before believing it.

→ Solution

Quick Reference

- **Climate:** the average and variability of weather over thirty years or more
- **Greenhouse effect:** gases absorb infrared and re-emit it; natural and capable of enhancement
- **Records:** thermometers, balloons, satellites, and proxies for the distant past

- **Natural variability:** orbit, sun, volcanoes, ocean cycles; attribution separates it from human influence
- **Reading a claim:** weather or climate, global or local, which period, what source, what uncertainty

Course complete

You have now followed the weather from the sun and the atmosphere through heat, moisture, wind, fronts, storms and forecasting, and finished by looking at the long view. Keep the habit that runs through every chapter: look up the figures marked "check" before you rely on them.