Meteorology and weather forecasting

Course materials for junior and intermediate secondary schools

Teacher materials and background information

General information on meteorology

The weather on Earth is governed by scientific laws – admittedly, very complex and imperfectly understood laws. This is why it is very difficult to forecast the weather for any one place, or over a protracted period, with the type of accuracy we associate with the exact sciences. Using more than 6000 weather stations on land, a network of globe-spanning meteorology satellites and modern technology based on powerful computers and sophisticated mathematical techniques are nonetheless able to provide very accurate one-day forecasts (86% reliability) and rather accurate three-to-seven day forecasts (80 % for 3-days). Beyond that, it is practically impossible to do so with reasonable certainty.

Satellites play an important role in predicting the weather, allowing us to monitor large expanses of the globe and study cloud formations, fronts, temperatures, composition etc. They allow us to see what happens to e.g. fronts during the night and analyse the distribution of water vapour in the atmosphere. Satellites can also give precise information about the concentration of trace gases (such as ozone) and air borne dust particles (aerosols), which are known to play a decisive role in determining the weather.

Global circulation (Chart 1/10)

All meteorological processes, including winds, the formation of clouds, temperature changes and precipitation, derive their energy from the sun's radiation. In the absence of solar radiation the Earth would rapidly cool down to the temperature of outer space and be transformed into an inert block of stone and ice.

The rate at which solar energy is absorbed on the surface of the Earth varies with the distance from the equator. In remote polar regions, an incident unit of solar radiation is spread across a much larger area than at the equator. For this reason there is much more energy available in the tropics. Seasons and the tilting of the Earth also play an important role.

The unequal distribution of energy is the main 'motor' driving circulation within the atmosphere. Absorbed solar energy is transported outwards from the tropical regions to higher latitudes, generating the wind systems that make up global circulation.

Weather basics

What we call weather takes place mainly in the lower thin layer of atmosphere surrounding the Earth's surface (troposphere and lower stratosphere). Much of it is shaped by a very few major mechanisms.

1. Air is exchanged along paths that run roughly north-south. This is because air heats up faster at the **equator**, where ground is exposed to the greatest amount of solar radiation (the sun doesn't heat the air directly, but the ground). The air heated from the ground beneath rises to a height of 15 to 20 km, where it cools off as it drifts outwards from the equator, before descending again as a much cooler air mass. The circulation system is completed when this air streams back

towards the equator at low altitude. What are called circulation cells are thus created. (See below and also on CD: pressure equalisation, trade winds, inter-tropical convergence zone ITCZ.

2. The **hydrologic cycle** is behind atmospheric phenomena such as cloud formation, front systems and precipitation. Water vapour is the atmosphere's most important greenhouse gas, and a prerequisite for life on Earth. Colossal amounts of water evaporate continuously in the equatorial regions of the Earth. After rising up by convection, clouds are formed. The air masses travel away from the equator and also form clouds.
   If the water vapour condenses, it falls to the Earth's surface as **precipitation**. Ultimately it returns to the equator in ocean currents, swelled by precipitation runoff that ends in the sea. Evaporation and precipitation involve huge amounts of energy.
3. On a continental scale, **heating and cooling cells** are responsible for low and high pressure zones (see: island model, onshore/offshore circulation). The air masses with different characteristics (pressure, humidity, temperature) form fronts and weather systems.
4. The rotation of the Earth, and the associated Coriolis forces (see on CD), make the weather patterns to move differently in the northern and southern hemispheres. In our hemisphere, the weather "moves" from **west to east**.
5. The immediate cause of weather is the **local imbalances** that exist in the distribution of temperature, humidity etc. The resulting processes, taken together, form the complex phenomena that make up our weather.

The Island Model / Offshore/Onshore System (Chart 2/10)

(Reminder: Pressure at a given level is the weight of the atmospheric column above it.) The island model is a good example of how vertical air movements work. In the morning, air above a land mass heats up much faster than above an adjacent body of water. It also heats up faster above an open field than above a forest, above a south-facing hillside faster than a north-facing one, above dry land faster than above wetland, etc.

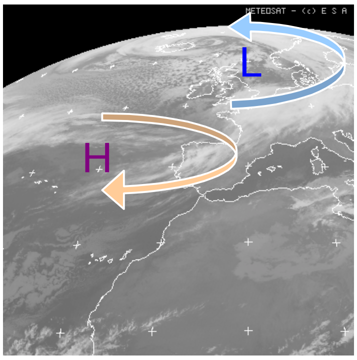
As the day progresses, local hot spots are created above the land, so that air tends to rise, while air above the neighbouring cooler regions flows there in order to maintain overall equilibrium. Where the air masses are rising, the air pressure will be diminished (lower density) somewhat, while where they are descending (higher density) it will be slightly higher. This explains e.g. the local breezes by the sea/lakes, which reverse at night.

Also, air masses characterised by more or less uniform characteristics of pressure, temperature and humidity, are modified when in long contact with continental or ocean areas. This, together with the large circulation cells, is the origin of the high and low pressure zones familiar from weather forecasters. They indicate

1. Geographical movement: how the air will be moving (winds) from lower to higher pressure areas,
2. Horizontal movement: when the pressure difference (gradient) is higher,

3. Vertical movement: ascending fast in low pressure areas, but being quite still in high pressure areas etc, which are crucial to understanding weather patterns.

Regarding the northern hemisphere (the following will be limited to it), Coriolis forces cause the wind in a low-pressure zone to spiral always in a **counter-clockwise** direction and in a high-pressure zone to spiral in a **clockwise** direction. (These effects are reversed in the southern hemisphere.)



High and low pressure zones are easy to spot. In a satellite picture the spiralling clouds are clearly visible, and if you compare several successive images you can see the direction of rotation. Clockwise rotation means there is a high-pressure zone at the centre of the zone, counter-clockwise means it is a low-pressure zone. The high pressure center area will be cloudless.

< Meteosat image showing clouds and fronts in visible light

Lift, convection, and the origin of clouds (Chart 3/10)

Water vapour is present throughout the Earth's atmosphere, as are suspended droplets of liquid water and tiny icy crystals. The highest concentration is in the lower atmosphere. The warmer the air, the greater the proportion of water in vapour form.). In some conditions, the vapour condenses at low levels, causing fog.

The rising air masses gradually cool down - in the troposphere around 1°C with every 100 m altitude. When the temperature approaches the threshold known as the dew point, water vapour starts to visibly condense out of the air. This process is accelerated if there are aerosols, i.e. tiny dust particles, to which the microscopic water droplets can adhere.

When this lifting is due to air heating from below, it is known as convection. If it involves only negligible exchanges of air and heat with the surrounding atmosphere we call it 'adiabatic' lifting. Large convection is the origin of storms, tornadoes etc.

Lifting can take place for other reasons, too. In 'orographic' lifting, air masses moving horizontally encounter an obstacle (e.g. a mountain range) that causes them to lift. This may cause a visible line of clouds to form along the mountain range, all at the same altitude. It also occurs when two different air masses meet (fronts).

An air mass that is very dry may remain clear despite being lifted, because there is not enough vapour in the air.

Clouds and rain (Chart 4/10)

Clouds are local regions of the atmosphere laden with suspended drops of water and ice crystals. When a cloud forms in an updraft, the smaller particles will be carried up by the air, while larger, heavier ones will fall downwards. If these water drops reach the Earth's surface, it's raining. However, on the way down, the water droplets may evaporate before they reach the ground (we see "virges" hanging underneath the clouds), or they may freeze and form snowflakes. Ice crystals precipitating out of a cloud may grow so large that they come down as hail.

Clouds associated with warm and cold fronts are not of the same type, due to the different way air will be lifted. Clouds are also often classified according to the height of their bases.

Typical cloud types of a **cold** front: Cumulonimbus, Cumulus

Typical cloud types of a **warm** front: Cirrostratus, Cirrus, Altostratus, Nimbostratus

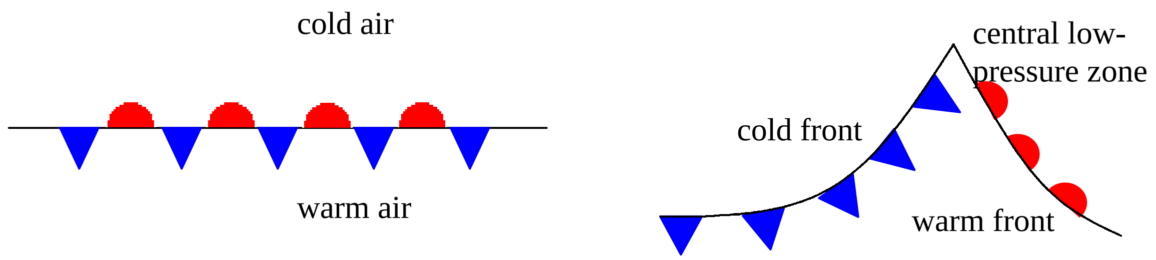
Pressure systems

The mid-latitude regions are marked by prevailing westerly winds that move a succession of low and high-pressure systems along those latitudes, causing typical variable weather. The pressure systems are essentially large rotating masses of air. A **low** is also known as a depression or cyclone, while a **high** is also known as an anticyclone.

Life and death of a mid-latitude cyclone (Chart 5/10)

Cyclones, depressions or low pressure systems, typically develop in mid-latitudes in a zone where warm tropical or subtropical air and cold polar air masses meet. European cyclones are usually generated above the Atlantic Ocean. The polar front is essentially stationary, and is marked by a steep temperature gradient from north to south.

Assuming this is the northern hemisphere, the result can look like this:

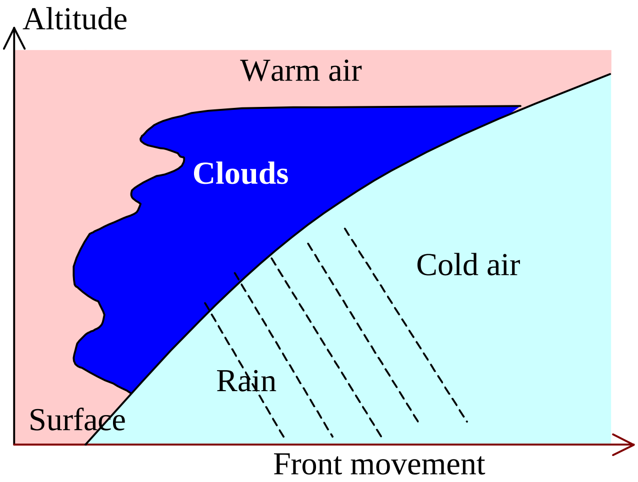


In this example there has been an incursion of cold air southwards and warm air northwards, creating a wave-like disturbance in the front (see right image above). Being locally unstable, it rapidly grows in size and intensity, until it forms a full-blown cyclone, featuring the typical arrangement of 'fronts': a **warm front** and a **cold front**.

When a warm front moves over a point on the Earth's surface, the effect on the ground is that cold air is gradually replaced by warm air; the opposite is true for a cold front.

Warm front

The air on the "warm" side of the front is less dense than the cold air on the other side, so it is buoyant and tends to rise. A cross section would show that the face of the front is inclined, with the warm air mass rising as the cold air mass advances. In the process, characteristic cloud formations occur that can be readily identified on satellite pictures.

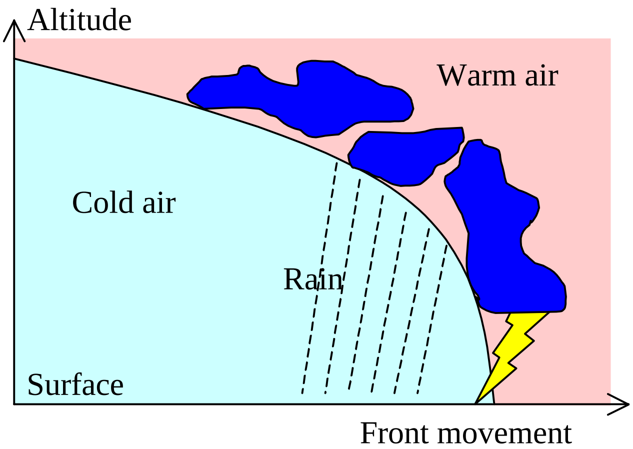


As the warm air mass rises, layered (stratiform) clouds form; they are associated with persistent but not very intense rain or snow.

The stratiform clouds along a warm front may be of different kinds: nimbostratus, altostratus, cirrostratus.

Cold front

A cold front is the region of a marked transition between warm and cold air. The effect of the successive movement of cyclones and their fronts is that, wherever a cold front has passed, warm air has been replaced by cold air.



The dense cold air advances, pushing the more buoyant warm air up, much as in the warm front. However, since cold fronts advance more rapidly than warm fronts, the angle here will be much steeper.

Low-pressure system in the summer (Chart 6/10)

Low-pressure system in the winter (Chart 7/10)

Important weather patterns (Chart 8/10)

Weather in Europe is dominated by certain standard types of weather pattern. Here are the three most common ones.

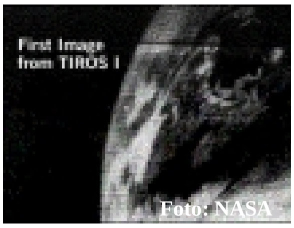
- **April**: cold air incursion. A major low-pressure system in the north of Europe, with its counter-clockwise rotation of air masses, brings cold polar air to the continent. Over the Atlantic Ocean the air mixes with water vapour. The combination brings cool weather to Europe, and copious precipitation – the proverbial April showers.
- **Summer**: high-pressure ridge. Two adjacent high-pressure systems above Scandinavia merge. Their clockwise rotation carries dry continental air from north-eastern Europe and Russia to central Europe. In passing above the continental region, the air heats up, providing typical warm and dry summer weather.

- **Autumn**: stormy low. A strong low-pressure system supplies Europe with a stream of relatively warm, moisture-laden air from the Atlantic. This air is very unstable, which is why late autumn is a time of unsettled and stormy weather. Note the closely-spaced pressure lines or 'isobars'. Close isobar lines indicate steep increase of pressure and thus strong winds).

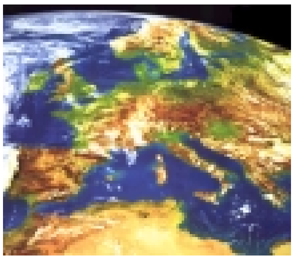
Meteorological data and weather forecasts (Chart 9/10)

People have been systematically recording and comparing meteorological data for some 250 years. Numerous ground-based meteorological stations provide comprehensive coverage of the land, and some sea-based stations also measure conditions at the surface. However, 71 % of the Earth's surface is covered by water. For Europe, the weather patterns that dominate the continent form far out to sea, over the Atlantic.

Meteorological satellites



On 1 April 1960 a new era started in meteorology with the launch of the first weather satellite, Tiros 1 (standing for Television and Infrared Observational Satellite). For the first time, a complete view was provided of the weather across the planet.



Europe's first weather satellite, Meteosat, was launched by the European Space Agency into orbit in 1977. Meteosat provided twice-hourly meteorological images. European weather forecasting has been completely transformed by the Meteosat satellites, of which seven have been built to date.

Meteorology satellites come in two types:

Polar orbiting meteorology satellites move in basically circular orbits, usually at an altitude of 800 to 1500 km, which are steeply oriented so that each orbit takes the satellite over the poles. Because the Earth is rotating about its axis at the same time, the result is that each point in Earth is covered by the satellite after a number of days that depend on such orbit..

Geostationary satellites orbit the Earth at the same angular velocity as the Earth's rotation, so they appear stationary seen from the Earth. This is done by positioning them above the equator, at an altitude of some 36 000 km. Meteosat is an example. It is positioned in the slot 0°E 0°N, i.e. vertically above the point where the Greenwich meridian intersects the equator, in the Gulf of Guinea off the coast of Africa. From this vantage point, Meteosat has a view of almost half the globe, including Europe, Africa, the Atlantic Ocean and parts of the Persian Gulf.

The current Meteosat already provides data that is useful in climate research, but once Europe launches Meteosat Second Generation (MSG), a quantum improvement is expected; with its higher spatial and temporal resolution, MSG will be able to observe very short-lived or highly localised processes.

MSG's advanced capabilities:

- Multispectral imaging with a refresh rate of fifteen minutes, twice as often as at present, rapidly providing data on local processes.
- Resolution in the broad visible spectrum will be improved from 2.5 square kilometres to one sq.km, providing finer images of cloud formation processes.
- Twelve spectrum bands are studied (instead of currently three). The visible spectrum being divided into three separately imaged bands (including near infrared) and the infrared spectrum into eight. In this way traces are detected in the atmosphere of substances such as ozone, which is profoundly linked to weather systems development. With 9 infrared bands of observation, weather processes can be studied which are invisible in ordinary light.
- Fast data transmission. MSG acts as its own communications satellite. The raw data is beamed to Earth, where it is processed by Eumetsat (European Organisation for the Exploitation of Meteorological Satellites) in Darmstadt, Germany. The results are transmitted back to MSG, which relays them to satellite receivers on the ground throughout Europe and Africa for the use of meteorologists, weather forecasters etc. With a data rate of over 3 Mbps, MSG is almost twenty times as fast as its precursor, the present Meteosat.

MSG was designed by the European Space Agency, ESA, and built by Alcatel Space (France), in a cooperative effort that involved thirteen European countries.

The European Space Agency created its Meteosat programme in the 1970s, with satellite construction, operation and data processing conducted by ESA until 1994, when Eumetsat took over. Today ESA is working on advanced technologies for new satellites, including MSG. The plan is to built three or four MSG satellites to be launched and operated by Eumetsat.. The operational lifetime of an MSG satellite is at least seven years.

The European Space Agency (Chart 10/10)

Founded in 1974, ESA has been the motor by which Europe established its presence in space, alongside the United States and Russia. The organisation counts fifteen member states: Germany, Austria, Belgium, Denmark, Spain, Finland, France, Ireland, Italy, Norway, the Netherlands, Portugal, the United Kingdom, Sweden and Switzerland. ESA's responsibilities encompass space programmes and advanced technology.

The principal activities of ESA are:

- <u>Space science</u> The Agency conducts exploration of the solar system and planets with probes and space telescopes, and studies conditions in the early universe. ESA's space missions play an important role in modern basic research.
- <u>Telecommunication and Navigation</u> Developing space technology and conducting non-commercial space missions has allowed European industry to develop world-class capabilities in a competitive industry.
- <u>Launch services</u> Advanced versions of the successful Ariane launcher are being developed, as is the small launcher concept (Vega). A French-registered

company, Arianespace, conducts space launches on a commercial basis. Ariane has captured almost 60% of the civilian payload market.

- Human spaceflight The Agency has developed and built important components of the international space station, such as a central computer system and a robot manipulator. In 2004 Europe's space laboratory Columbus will be installed, allowing up to three scientists to conduct experiments in microgravity.
- Earth observation ESA's purely civilian mission has allowed Europe to make great advances in scientific monitoring of the environment. The new Earth observation satellite, Envisat (a follower of the successful ERS series) , collects data about atmospheric ozone, trace substances, greenhouse gases and carbon dioxide. It measures the temperature of land and sea, the level of the ocean, the receding Arctic ice cap and industrial nitrous oxide emissions. The prolific measurements and data Envisat is collecting also cover movements of the Earth's crust, volcano eruptions, seismic events, flooding, drought areas and more.

This educational package was developed by the European Space Agency. ESA is a European organisation based in Paris, with establishments in Noordwijk (Netherlands), Cologne and Darmstadt (Germany) and Frascati (Italy).

This package is provided free of charge for instructional purposes. A separate CD-ROM, entitled "The Weather Machine", provides more information. It is available in three languages (English, French and German) and may be obtained free of charge. A VHS video (PAL) explaining the MSG mission is also available on request.

If you are interested, please contact:

- ESA ESOC, Jocelyne Landeau-Constantin, telephone +496151-902696
- or visit the ESA site at **www.esa.int**

The course material was created by Ludwig Lenz, Jean Le Ber, Eva Oriol-Pibernat and Adam Majorosi based on texts and images taken from various sources, including the CD-ROM "The Weather Machine" © 1997 ESA. Content: ESA 2002