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Air in motion

Introduction

The air is in constant motion. The engine of atmospheric circulation is the Sun, which warms the Earth and the air of the atmosphere differently, depending on the latitude. The atmosphere tries to rebalance the temperature differences by moving masses of hot air from regions where there is an excess of heat towards colder regions. The movements of air masses that seek to rebalance the differences in temperature and pressure in the atmosphere give rise to winds, cyclones and anticyclones and to all those weather phenomena that make the atmosphere of our planet "turbulent".

Atmospheric circulation

Moving masses of air

It is difficult to construct a model of atmospheric circulation, because very many factors influence the displacement of masses of air through the atmosphere; however, the fundamental principle is that the gases that make up the atmosphere tend to seek a condition of equilibrium that implies a uniform distribution of energy, equalizing the temperature and the pressure on the entire planet. The ‘motor’ of atmospheric circulation is therefore given by the redistribution of the energy received from the Sun. Solar radiation, in fact, varies at different latitudes with the result that the equatorial regions are warmer than the polar ones. The atmosphere tends to re-balance this difference moving masses of warm air from the regions where there is an excess of heat towards colder regions, in an attempt to reduce the difference in temperature between the Equator and the Poles.
Differences in temperature bring about immediate differences in the pressure within the masses of air: it is these differences in pressure that cause air displacement. Low pressure areas attract air from areas where the pressure is higher. Vice versa, air tends to move away from high pressure areas towards areas with lower pressure. The speed at which this displacement takes place is directly proportional to the difference in pressure between the two points. In ideal conditions, if the Earth were motionless and if there were no friction or obstacles, air would flow perpendicularly to the isobars (the lines that join points with equal pressure), according to the so-called pressure gradient, following a path that makes the air travel along the shortest route from the high pressure area to the low pressure one. However, many factors contribute to deviating the flow of air from the ideal condition.

The Coriolis effect

The Coriolis effect, that gets its name from the physicist Gaspard Coriolis who postulated the theory in the 19th century, is an effect, caused by the Earth’s rotation, that acts on moving bodies on the Earth’s surface. It is also known as Coriolis force, but this definition is incorrect since it is not really a force, even though its effects may appear similar to those of a force to an observer within the system. As a consequence of the Earth’s rotation, any object that travels in a straight line will undergo a deviation in its path that will take it far from the desired point unless it can carry out continuous changes in its course. In the Northern Hemisphere, every moving object will tend to drift towards the right, while in the southern hemisphere it is towards the left. To an observer within the system, it may seem that there is a mysterious ‘force’ that pushes objects off their course, but in actual fact, it is an effect caused by ‘displacement’ of the Earth’s surface under the moving object.
The Coriolis effect is proportional to the angular velocity of the Earth (that is constant), to the speed of the moving object and to the latitude: it is null at the Equator and maximum at the Poles.
This effect can be observed in many daily situations: in the Northern Hemisphere aeroplanes have to change their course towards the left, the right railway track undergoes a greater wear, etc... Similarly, even winds undergo deviations: if the Earth were motionless, the winds would tend to move in a N-S direction, from the Equator to the Poles along the meridians, but as a result of the Coriolis effect, winds from the North tend to become winds from the NE and so on.

High and low pressure

If an isobar chart is observed, it can be seen that pressure is not distributed uniformly in the atmosphere around our planet: there are areas with a lower pressure than the surrounding areas and areas where the pressure is higher. Due to a characteristic of gases, air tends to move from high pressure areas towards those with low pressure in an attempt to balance the difference. The presence of high and low pressure areas is therefore the principal motor of all meteorological phenomena, in other words, of the 'weather'. Hence, it is important to understand how air circulates close to these areas (see graph) and how they are distributed in the atmosphere.

Anticyclones

In high pressure zones, air tends to sink towards the ground causing the air that is present to move away with a divergent movement. The air gets compressed while descending and tends to disperse the clouds, and in fact high pressure conditions are associated with settled and calm weather. As a result of the Coriolis effect, air tends to move away from the high pressure system, clockwise in our hemisphere and anticlockwise in the Southern Hemisphere (anticyclonic circulation).

Cyclones

A low pressure area, instead, tends to attract air from the surrounding region where the pressure is higher. Near the centre of the cyclone, air tends to rise higher attracting a growing amount of air from the neighbouring areas. On rising, air expands and cools with the subsequent formation of clouds and precipitation: it is for this reason that low pressure areas are usually associated with bad weather. Air tends to converge towards the low pressure centre with an anticlockwise movement in our hemisphere and a clockwise movement in the Southern Hemisphere (cyclonic circulation).

Circulation cells

Temperature and pressure differences are not distributed casually in the atmosphere but permanent and stable low and high pressure areas can be identified, which are organized so as to form big circulation cells around the world. This situation, obviously, is not static and unchangeable. During the year the circulation cells move towards the North or the South, depending on the unequal amount of solar energy that the different regions of the Earth receive in each season: in our hemisphere, they move towards the Equator in winter and towards the Poles in summer.
Three main circulation cells can be identified in each hemisphere that are placed symmetrically respect to the Equator.

When air masses meet

When a moving cold air mass meets a warm air mass, that is lighter, it tends to wedge below the latter, thus giving origin to a cold front. The warm air is forced upwards and its ascent causes the formation of clouds. Since the surface of contact between the two masses is quite steep and ascent is rapid, the clouds will be prevalently of the cumuliform type. The passage of a cold front is accompanied by widespread cloud systems and precipitations, with a sharp drop in the temperature, an increase in the pressure and precipitations often characterized by thunderstorms.
On the weather charts, cold fronts are indicated using a black line with triangles. Cold fronts form typically at our latitudes, when the cold dry air from the Polar regions meets the humid air coming from the tropical regions.

Warm fronts

If, on the contrary the warm air mass is moving towards the cold air mass, the warm air mass slowly slips over the cold one, and rises along a vast gently sloping surface: in this case we can speak of a warm front which also brings clouds and perturbation systems. The margins of a warm front are less marked that those of a cold front, changes are more gradual and the perturbations arrive less rapidly. The passage of a warm front is marked by a rise in the temperatures, a decrease in pressure and persistent rains, which are however of a moderate intensity. Since the clouds rise slowly, the cloud system that forms generally consists of stratified clouds. On the weather charts, warm fronts are indicated with a black line with semicircles.

Occluded fronts

An occluded front forms when a cold front reaches a warm front, forcing all the warm air to rise to higher altitudes and the cold air is stratified near the ground. At our latitudes, over the Atlantic, cyclonic areas form continuously, these are fed by

the Azores anticyclone and the Polar anticyclone. Here, the tropical warm and humid air and the cold dry polar air meet, and generally a depression vortex is formed in which a warm front and a cold front are active. The cold front is generally more active and advances more rapidly than the warm front. When the cold front reaches the warm front an occluded front is originated. After having discharged the remaining humidity on to the occluded front, the weather generally returns to good weather, the air on the ground starts to warm again: and the perturbation is exhausted.
On the weather charts occluded fronts are indicated with a black line with alternating triangles and semicircles.
Perturbation front
The presence of mountain ranges on the course of a front can provoke variations and deformations of various types, that can lead to evolutions in a perturbation that are difficult to forecast.

Circulation cells

Between the Equator up to 30° latitude (N or S), we find the Hadley cell.
In the Equatorial region, air is heated and rises, creating a low pressure area. Air would tend to shift towards the N along the meridians, but in the northern hemisphere, due to the Coriolis effect, the flow is deviated towards NE and descends toward the 30° parallel, bringing warm humid air. Once it descends, the air is again drawn towards the Equator due to the low pressure of the area, and this time the air travels from NE to SW, again as a result of the Coriolis effect. This movement gives origin to the NE trade winds. The same occurs in the southern hemisphere where the trade winds blow from the SE. The area where the NE trade winds clash and converge with the SE trade winds creates an equatorial low pressure area characterized by precipitations and violent perturbations, the so-called area of equatorial calm, that gets its name due to the low pressures and low wind speeds. Between the 30° and 60° latitudes, instead, in both hemispheres the Ferrel cell is active. It rotates in the opposite direction to the Hadley cell. Converging with the margin of Hadley's Cell, a tropical high pressure area is created, around 30°, the so-called horse latitudes area, where the winds blow from the SW on ground, the westerlies which however have a more irregular trend than the trade winds. In this belt there are a series of anti-cyclonic nuclei, among which the Azores anticyclone whose seasonal movements determine the weather in our regions. The masses of air from the Ferrel cell move back to the higher altitudes around the 60° latitude, where the area of sub-Polar low pressure is formed.
In the higher latitudes the Polar cell forms, which has the same trend as the Hadley cell with easterlies at ground level and westerlies at higher altitudes. The Polar cells are the least extended, but thanks to the Polar high pressures, these have the important task of transferring the freezing polar air to the middle latitudes in the Ferrel cell.

Winds

What they are

Winds are more or less rapid horizontal displacements of air masses caused by differences in the pressure distribution. Due to the fact that pressure variations are mainly caused by temperature variations, it follows that the wind's main motor is the divergence in solar radiation in the different regions of the world.
Wind direction
Each wind is characterized by the direction in which it moves and by its speed. Normally, when one talks about wind direction, one means the direction the wind comes from: westerly winds, for example, are winds that blow from the West to the East.
Air masses would tend to move perpendicularly to the isobars, following the pressure gradient, i.e. the difference in pressure that brings about the displacement of masses of air, but the Coriolis effect modifies their course. In ideal conditions in which there is no friction, and in which the pressure gradient force and the Coriolis effect are equal and opposite, winds move parallel to the isobar lines, leaving the high pressure areas to their right in the Northern Hemisphere and to their left in the Southern Hemisphere: these are the so-called geostrophic winds, winds that are 'ideal' so to speak.

Generally, at ground level, friction with the Earth's surface causes deviations in the wind's direction and only winds at an altitude greater than 1,500 m are very similar to geostrophic winds.

Winds at ground level

Winds can be divided into ground level winds, that blow in the lower strata of the troposphere, and high altitude winds.
As far as winds at ground level are concerned, different types can be distinguished: local periodical winds, such as coastal and valley breezes, that form as a result of the unequal heating caused by unequal solar radiation, and global winds, whose direction and intensity depend on the distribution of the big pressure cells in the world.
The trade winds blow from the subtropical anticyclonic cells towards the equatorial low pressure areas. These winds are very steady and their direction is E-NE in our hemisphere and E-SE in the Southern Hemisphere.
From the northern flank of the same anticyclonic cells the westerlies blow, flowing from SW in the northern hemisphere and from NW in the southern hemisphere. The easterlies, instead, come from the internal Polar regions and meet the westerlies in the subpolar low pressure areas. As the seasons change, the pressure systems change and so do the winds.
In addition to the global wind systems there are local systems, even on a vast scale, such as the monsoon winds (from the Indian word mausin that means season) that are seasonal winds caused by the unequal heating of continental and oceanic areas.
The winter monsoon winds that are cold and dry blow from the Asian continent towards the Indian Ocean, while the summer monsoon winds blow from the ocean towards the continent carrying humid, warm air accompanied by particularly intense, at times catastrophic, precipitations.

High altitude winds

In theory, one might expect ground level winds to be coupled with similar winds, blowing in the opposite direction, at high altitudes, in the higher strata of the troposphere. In practise, however, from observations that have been carried out, it has been shown that above an altitude of 4-5.000 m there are only westerly currents that move from West to East roughly following the route of the parallels. Only above the Equator there is a narrow band of easterly winds that are probably connected to the convergence zone of the trade winds.
The speed of high altitude winds is proportional to height. The greatest speed is reached at the limit of the troposphere. These winds are slower at the Equator, they grow in speed at the middle latitudes and slow down again closer to the Poles.
It is not quite clear as yet which is the mechanism that brings about this type of circulation at high altitudes, but, whichever the origin, the role of high altitude winds is fundamental in the distribution of cyclonic and anticyclonic areas in the world.

The Foehn wind

The name Föhn (or Foehn) comes from the dialect of Tyrol, and indicates a particular type of wind that is characteristic in the Alps, which can also be noted, naturally, in most of the other mountain ranges. It is generated when a moving mass of warm humid air meets a mountain on its path. By inertia, the mass of air moves against the mountain and the air is forced to rise along the sides of the mountain. As it rises, the air cools and expands, thus becoming saturated with water vapour. Clouds are formed and the excess humidity is released in the form of abundant liquid precipitations or snowfall. Because of the heat that is freed during the condensation, the air that rises to the peak of the mountain is at a higher temperature than what it would have been had it been dry. When it passes the mountain crest, after having discharged most of its humidity, the air that is now dry, blows across the opposite side of the mountain and becomes warmer as it descends. In the Alps, masses of air rise along the northern slopes (Switzerland and Austria) , with the formation of clouds and precipitation, and the warm air descends on the Italian slopes, where the weather conditions become fair, with clear blue skies and temperatures that are 10-20° C higher than on the Northern slopes. This phenomenon guarantees winter days that are mild and very clear in Northern Italy, with strong winds that blow away the fog and

pollution that hover above the big cities due to inversion, while on the other side of the mountains, the weather conditions are bad.
This phenomenon explains why snowfall is generally more plentiful on the northern slopes of the mountain range. This type of atmospheric phenomenon is very dangerous in case of heavy snowfall, because since it favours high temperature conditions, it also brings about the melting of the layer of snow and increases the risk of avalanches. Therefore, skiers must pay attention on clear winter days that are unexpectedly warm. And if you leave Milan on a wonderful clear morning, to ski on the Swiss snow, be careful. If the mountain crests at the frontier are capped with thin feathery clouds, swept by the wind, you may find bad weather conditions awaiting you on the other side! However the Foehn's misdeeds are not limited to this; when the warm dry air that travels at a high speed is blown over the mountains, the wind has the capacity to charge the air with electricity, increasing the number of positive ions. Our body reacts negatively to positive electric charges, and in "meteoropathic" subjects who are particularly sensitive to the variations in the weather, this provokes nervousness, anxiety, migraine and irritability. A statistical study carried out in Switzerland, where this wind is called Favonio, correlated the days of Foehn winds with an increase in the number of suicides, homicides and aggressions.

Jet streams

Jet streams are particular evolutions of high altitude winds. They are rapidly moving air currents caused by pressure differences that result from the temperature divergences that occur when big air masses meet. They were discovered fortuitously by American aeroplanes flying towards Japan during the Second World War. To be called a jet stream, the wind speed has to be higher than 50 knots, about 90 km/h, however, jet streams usually have much greater speeds ranging from 160 to 250 km/h, with peaks of 320 km/h. Generally, these winds are stronger during the winter because temperature differences are more marked. They form at altitudes of about 10-14 km. They tend to form at the boundaries between hot and cold masses of air, along the so-called fronts: in these areas distinct variations in the isothermal and isobaric surface gradients can be found and it is along these surfaces that the winds tend to move with greater speed. Jet streams surround the globe forming kinds of 'belts' around the planet following the parallels. Their trend is not straight and this causes descending movements towards the equatorial zones (wave troughs) and ascending movements towards the Poles (wave ridges). Ridges and troughs move, change and evolve continually.

The effects of jet streams

In our hemisphere, there are two main jet streams in winter: the Polar Front jet stream, above Canada and northern United States, and the Subtropical jet stream, over northern Mexico. Both these winds move from West to East. A third wind, that moves from East to West, forms in summer, instead, over Africa and India and is partly responsible for the summer monsoon. In the Southern Hemisphere, on the other hand, only two westerly jet streams are present.
Jet streams influence air navigation, making the same route take more or less time depending on whether the aeroplane travels with a head or tail wind: the return journey from the United States towards Italy is generally approximately one hour shorter respect to the outward trip. But the most important feature of jet streams resides in their influence on climate. Where there are wave troughs, in fact, high pressure areas form; where there are the so-called regions of convergence, there are zones where the speed of the flow decreases. As a result of the Coriolis effect, the latter are transformed into anticyclonic cells, with dry, fair weather at ground level. On the contrary, where there are wave ridges, a low pressure area forms; where there are regions of divergence, there are areas where the speed of flow increases. These zones are transformed into cells with a cyclonic circulation that bring bad weather at ground level.

Clouds

What they are

Clouds are formed by microscopic drops of water or by small ice crystals. The size of the droplets generally range from a couple of microns to 100 microns: this is the limit beyond which cloud drops become rain drops. The shape of the drops is usually spherical, but it can vary, especially in bigger drops that are deformed by gravity.

Water in the atmosphere: evaporation and condensation

The evaporation of water bodies and evapotranspiration from soil and vegetation supply the atmosphere with great quantities of water vapour. Even though it is abundant, the amount of water vapour supplied to the atmosphere by evaporation processes generally is not sufficient to make the air reach saturation point. Saturation and the consequent condensation of vapour into drops of liquid water are therefore generally caused by the cooling of air masses at a temperature below condensation, also known as dew point. When condensation takes place, a part of the excess water vapour changes from the gaseous state to the liquid state, forming microscopic drops of water. For condensation to occur, however, it is not sufficient to reach the dew point: it is necessary that the so-called condensation nuclei should be present. These are small particles (whose dimensions range between 0.001 and 10 micron) on which the tiny drops of water can condense. The condensation nuclei normally present in the atmosphere are sodium chlorides, sulphates, carbonaceous particles and atmospheric dust and can be present as a result of natural causes (as for example, marine aerosols transported by the wind or ashes coming from volcanic activity) or due to human activities (the result of the combustion of fossil fuels, for example). The bigger and more hygroscopic (i.e. capable of attracting water molecules) the nuclei are, the more effective is their role in favouring condensation processes.
If the temperature is low, water condenses in the form of ice crystals, but it still requires the above-mentioned nuclei that, in this case, are called crystallization nuclei.

Cloud formation

Cloud formation is apparently a very simple process, caused by the condensation of atmospheric humidity into drops of water, but in actual fact it is a more complex phenomenon, in which different factors and mechanisms are involved. All the processes however are based on the ascent of a mass of humid air and its successive cooling up to dew point.
In this process a body of water or the humidity of the ground evaporate as a result of solar radiation and a volume of hot, humid air forms and slowly starts to rise since hot, humid air is lighter than the air surrounding it. As it rises two factors act on the mass of air: the decrease in pressure makes the air expand and the decrease in temperature, due to the higher altitude, cools it until it reaches dew point: the air mass is saturated with water vapour and this condenses into small drops of water in its liquid state. A cloud is the visible expression of this process. The condensation process is favoured if particles and impurities are present that can act as condensation nuclei on which the droplets can deposit. If these are absent, the air mass can become over-saturated with water vapour.

How they move

The contribution of the Sun: lifting by convection

Solar radiation is the first and most evident cause of the lifting of warm and humid air masses: the air gets heated both by direct absorption of solar radiation (especially in the infrared band, that is preferentially absorbed by water vapour), and by convection above the ground that loses heat.

The contribution of the mountains: orographic lifting

The process is analogous to the previous one, but in this case, the mass of warm and humid air rises because of the topography: when a moving mass of air meets a mountain it is forced to move along its sides, rising and cooling.

Air masses meet: dynamic lifting

Even in this case, the mechanism is the same, but the lifting takes place because a mass of air is pushed upwards by another moving mass that wedges itself under it. Generally this occurs when a warm, lighter mass of air meets a cold air mass that, being denser, tends to wedge itself under the warmer air forcing it to rise.

Stratified air: thermal inversion

In fair and stable weather conditions, especially in winter, cold air tends to stratify close to the ground giving rise to the phenomenon of thermal inversion: in this case, the temperature of the air rises with altitude instead of diminishing, as it does normally. In this circumstance, it is the warm air that cools on contact with the cold mass below: if dew point is reached, thin layers of clouds might form, that ‘materialize’, so to speak, the boundary between the two distinct masses of air.

Different shapes

The first scientific classification of clouds was made by an English chemist, L. Howard, in 1803, and the classification system that he proposed is, with some modifications, still used today. It is based on two principal groups, divided according to the development (vertical and horizontal) and three types: cirrus, cumulus and stratus clouds. The different combinations of groups and types lead to the different cloud formations.

Different shapes

Stratus (St) clouds, are widely extended horizontal sheets in the lower elevations, and are generally grey. They seem to cover the sky in a uniform manner at various levels. The thickness of the stratus cloud can vary from 15 to 800 km. Their regular shape and surfaces are due to the fact that within these clouds there are no internal convective phenomena, which give clouds bizarre shapes. Also fog banks belong to this category. These clouds can bring drizzles or light snow.
Cumulus (Cu) clouds, are dense clouds with a marked outline. They have a typical flat base that starts to form at altitudes around 1,800 m, that indicates the elevation of the level of condensation. The upper part that can reach considerable heights instead is swollen and irregular due to the internal convectional movement. The base is generally dark, while the higher parts of the cloud are white and brilliant. Cumulus clouds are generally a sign of good weather conditions.
Cirrus (Ci) clouds are the typical high altitude clouds, they are formed by ice crystals which characterize their evanescent fibrous shape. Often these clouds provoke precipitations, however, since they are situated at very high altitudes, the precipitation generally evaporates before reaching the ground. Due to the effect of refraction of light in the ice crystals, cirrus clouds form iridescent halos around the Sun or the Moon. Often these are indication of a warm front or a storm system. Nimbus (NB) clouds are dense clouds with a strong vertical development, with towering forms. The lower part of these clouds is dark and jagged, the upper part is generally swollen and continuously evolving. These clouds are dark and gloomy, they always bring precipitation and often they move at great speeds along the bad weather front.
The main types of clouds can be combined together thus obtaining more complex forms:
cumulonimbus (Cb) clouds that are dense and have a strong vertical development. These clouds bring precipitation and showers in the form of storms. When the upper part reaches the limit with the stratosphere, the top of the cumulonimbus clouds becomes flattened, thus taking on the typical anvil shape;

- stratocumulus (Sc) clouds, in banks, formed by rounded grey coloured masses, with darker parts, generally produce light rain;
- nimbostratus (Ns) clouds, are grey, dark, not clearly defined shapes, due to the precipitation that accompanies them;
- altocumulus (Ac) clouds consist of white rounded masses that are often arranged in a regular , tidy manner, known as “cielo a pecorelle” sheep-shaped clouds in the sky;
- altostratus (As) clouds are grey or bluish extended clouds, with a fibrous, striped appearance, and are formed by drops of water and ice crystals that can give rise to continuous precipitation;
- cirrocumulus (Cc) clouds appear in thin transparent banks and are sometimes arranged in striped bands;
- cirrostratus (Cs) clouds are shaped like whitish fibrous veils.

Different altitudes

Low clouds reach a maximum limit of 1,800 m, while the low limit can even be at ground level. Stratus, nimbostratus, stratocumulus and cumulus clouds belong to this category.
Average clouds are to be found at elevations ranging between 2,000 and 6,000 m. Altostratus and altocumulus clouds belong to this category, but at these heights we often find clouds that are moving from the lower layers to the higher

ones.
High clouds can reach the limit of the troposphere. They consist mainly of ice crystals and not drops of water due to the low temperatures. Cirrus, cirrocumulus and cirrostratus clouds belong to this category.

Clouds as indicators of the weather

The shape of the clouds depends on the process that formed them, and by the movement of the air within them and in the surrounding zones. Therefore they can be indicators of the meteorological conditions and can be a valid help in short-term weather forecasts.
When the air is humid and unstable, generally cumulus and cumulonimbus clouds are present, instead, when the air is dry and stable, they tend to be lenticular. If the air mass lifts slowly and regularly, the clouds that form are generally stratified, if instead, it lifts rapidly, cloud development is prevalently vertical, as in cumulus and cumulonimbus clouds. If the air is very humid and unstable, the air mass is lifted very rapidly and the cloud has a towering shape. The upper part rapidly and constantly changes due to the internal convective movements, but once it reaches the limit of the stratosphere, it flattens like an “anvil” and stops rising, this is the characteristic form of cumulonimbus clouds that are always carriers of precipitation, which may even be rather violent.