SNEŽANA BULAJIĆ
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THE GUIDE TO METEOROLOGY AND ATMOSPHERIC PHYSICS FOR HIGH SCHOOL AND FRESHMEN STUDENTS

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FOREWORD

Internationalisation of science and education contributed to exponential increase in scientific knowledge in the second half of the 20th century. Emergence of the Internet and social networking increased the scope of information exchange to the highest possible level in the history of mankind and provided the acquisition of the highest levels of knowledge in the most distant parts of the world.

National borders have almost disappeared at the university level. But, does the present schooling system train students in secondary schools to explore the world of universities without borders? Apart from high quality acquired knowledge of basic sciences and arts, open mindedness and readiness for dialogue, the knowledge of current world issues is also necessary for their future professional orientation.

The right time for the change in the educational paradigm has already arrived. The plans and programmes for certain subjects, as well as the textbooks for those subjects are only rough drafts instead of precise instructions for the teaching process.

The aim of this publication is to explain the topics in meteorology and physics to the students and teachers of physics in secondary schools in a recognizable way and to introduce some of the most current scientific challenges (mechanism of greenhouse gases, causes and effects of climate changes) into the teaching process of physics subject in secondary schools. Moreover, the book may also be useful for the university students, who need to pass the course in Meteorology, to bridge the gap between the acquired knowledge in secondary school and prerequisites needed for successful mastering the topics in Meteorology.

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YEAR

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Thematic unit:

FORCE. BASIC PRINCIPLES OF ROTATION DYNAMICS.

Training units:

1. Friction
2. Pressure gradient force
3. Centrifugal force
4. Coriolis force

Atmospheric circulation and winds

There are various forms of what is referred to as wind: firstly, constant air circulation around the Earth, secondly, local breezes, thirdly global winds and finally general air circulation. Wind is horizontal air movement from areas of higher to areas of lower air pressure. Pressure differences, either global or local, force the air mass to move. Regardless the cause of the air pressure difference, it is the main driving force that drives the wind. The forces in the nature regulate the winds and terrain configuration modifies the winds. Atmospheric circulation occurs as a result of force actions such as: Coriolis force, centrifugal force, friction and pressure gradient force.

Forces acting upon the atmospheric motion

Friction. Friction occurs when two objects are in immediate contact and it opposes the motion of *two* contacting bodies, with respect to each other.

When two solids are in contact, we talk about *external friction* which is the consequence of roughness of both objects and forces with which bodies act upon each other. When we talk about the interaction of layers within the same fluid (liquid or gas), then we say that there is *internal friction* between them. Similarly, when a solid moves through a fluid there is *resisting force* which may be considered a special type of friction.

The occurrence of internal friction between the fluid layers while in motion is called viscosity, and tangential forces that appear during the process are called viscous forces. Viscosity phenomenon observed from the point of view of molecular physics is explained by interaction of molecular forces and thermal molecular movement. Groups of molecules move from layer to layer and cause the change of impulses in layers which in certain time interval represents the viscous force of layer interaction. The viscosity of gases is lower than that of fluids since intermolecular forces are of lower intensity in gases.

Due to internal friction the layers of fluids move at different velocities and the viscous force has the same direction, but opposite to the direction of fluid movement. In case when velocity of layers drops linearly to zero along the normal to the fluid direction then *Newton's Law of Viscosity* is valid:

$$\mathbf{F_v = \eta S(\Delta v/\Delta z)},$$ where:

F_v – viscosity force

S – size of the contact surface between layers

η – coefficient of fluid viscosity

$\Delta v/\Delta z$ – velocity gradient along the normal to the movement direction

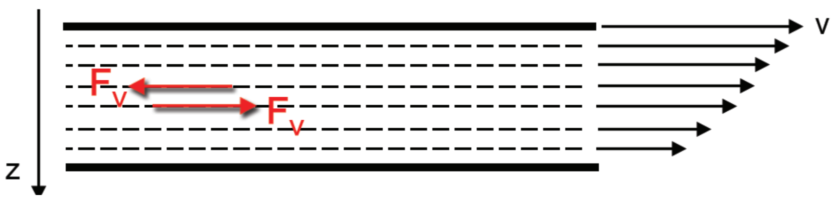

Figure 1. Velocity gradient of fluid layers above solid surface along the magnitude normal to the direction of movement

Friction occurs when lower air masses approach the obstacles such as hard surfaces (relief) and atmospheric layers in Earth's atmosphere. Friction force direction is the opposite to the air flow direction of movement. Friction force only acts on a thin layer of air which is in contact with hard surface. The reason for this is low air viscosity, and that layer is called viscous layer. Friction force increases with the increase of airflow velocity and also depends on the structure of hard surface, i.e. its roughness. If the roughness of the surface increases, the friction also increases and therefore, this force is higher above mountain massifs than above water surfaces. In addition, according to the Newton's Law of Viscosity friction decreases when the altitude increases and it decreases faster if the surface is flatter. For example, atmospheric layer in which the friction action is felt is incomparably thicker above the mountain massifs (2-3km) than above the oceans (about 100m). In meteorology the atmospheric layer in which the impact of friction force is felt is called *friction layer*, and the part of atmosphere in which the impact is not felt is called *free atmosphere*.

Gradient pressure force. Atmospheric pressure is created by the force of air acting on a certain surface. Due to the difference in pressures between two points on the horizontal line, the air movement will start from the point in which the pressure is higher towards the point in which the pressure is lower. It is said that the pressure gradient of vector character occurs..

The force that leads to air movement due to the pressure gradient is called gradient pressure force whose direction is the same as the direction of pressure gradient. As mathematical unit, gradient is always directed towards the increase of physical size, thus gradient pressure force will always have the direction which is opposite to the direction of pressure gradient.

$$\mathbf{F_x / \Delta V = -(\Delta p / \Delta x)}$$

where:

$\Delta p/\Delta x$- horizontal pressure gradient along the x-axis

ΔV- unit volume of air

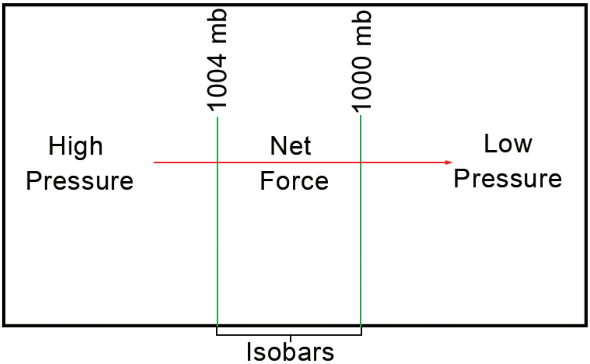

Figure 2. Direction of gradient pressure force

Horizontal gradient force pressure is important since it represents the initial cause of wind, whereas other forces, such as friction and Coriolis force start acting when air movement is already present. Therefore it is important to know how horizontal gradient force originates.

For example, we may observe atmospheric layer above the sea and above the ground immediately before the sunrise. At that moment the temperatures of the ground and the sea are equal. At any altitude, measured with regard to the sea level, the pressure above the ground and the pressure above the sea are also the same. That means there is no horizontal pressure gradient; therefore there is no air movement from the ground to the sea and vice versa.

During the sunrise the ground and the sea start warming, the ground warms at higher speed because it has lower specific heat capacity than the water. The temperature above the ground increases more than the temperature above the sea and horizontal temperature gradient is formed. The air above the ground is heated by convection and conduction; it becomes thinner and rises up. Thus, due to the arrival of new air mass, higher pressure is formed at certain altitude above the ground compared to the pressure that is formed at the same altitude above the sea, i.e. horizontal pressure gradient is created in this way. Consequently, the air above the ground moves towards the area above the sea, the area with lower pressure, i.e. air circulation starts from the ground towards the sea.

Furthermore, certain air mass has moved upwards, the density of the air column near the ground has decreased and the pressure has dropped in that part. That is how the second horizontal pressure gradient is formed due to which the air from the sea moves towards the ground, i.e. from the area of higher air pressure to the area of lower air pressure. That is, when the temperature difference is created between the two locations where the air has been previously calm, the temperature difference causes two parallel movements of the air but in the opposite directions, the first one at a higher altitude and the second near the Earth's surface (Fig. 3).

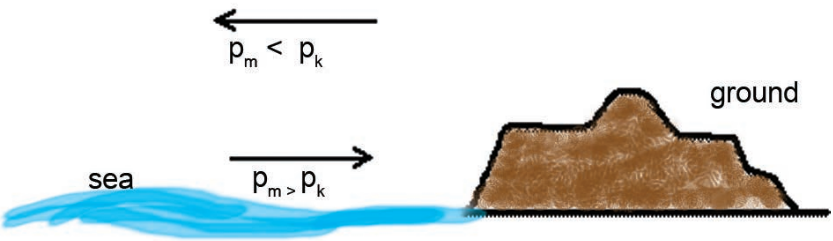

Figure 3. Air movement towards the ground and towards the sea during the sunrise

Centrifugal force and Coriolis force. The planet Earth rotates around its axis has normal acceleration and represents a non inertial frame of reference (non inertial frames are frames which have non-zero acceleration). According to the Law of Inertia, every object on the Earth is acted upon by a force that will cause the object to follow rotational movement of the Earth. Inertial forces act upon objects in non inertial frames of reference, the intensity of the forces depends on the object's mass and acceleration of the non inertial frame of reference, whereas the direction of the forces is opposite to the direction of the non inertial frame of reference.

When we observe the objects related to the Earth or in contact with the Earth, inertial forces do not act upon the objects since the Earth forces the objects to move together with it due to the aforementioned relations. However, in case of fluids, such as the atmosphere or water in hydrosphere, there are consequences of accelerated movement of the

Earth such as the impact of inertia force on the form of their movement path. It has been established that, due to the rotation of the Earth around its axis, two forces occur: centrifugal force that acts on both moving and stationary objects with regard to the Earth, and Coriolis force that acts on objects only if they move with regard to the Earth.

Centrifugal force is inertial force whose direction is normal to the rotation axis of the Earth and its direction of movement is "away from the axis of rotation". Since all the parts of the air are acted upon by the Earth's gravitational force, which also has the role of centripetal force (direction of motion towards the centre of the Earth, direction of the radius of the Earth), all parts of the air are constantly under the impact of gravitational and centrifugal force (Fig. 4).

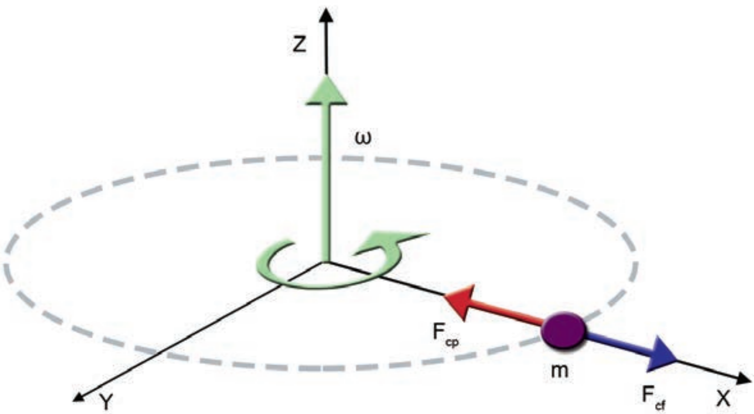

Figure 4. Direction and movement direction of centrifugal and centripetal force

$$F_{cf} = m\omega^2 R\cos\theta$$

where R-radius of the Earth, and θ- the angle that the position vector forms with the equatorial plane (latitude)

Coriolis force occurs only when the air moves and the consequence of this force acting is the curving of the force's straight line path.

Magnitude of Coriolis force is defined by the formula:

$$F_k = 2mv\omega\sin\theta$$

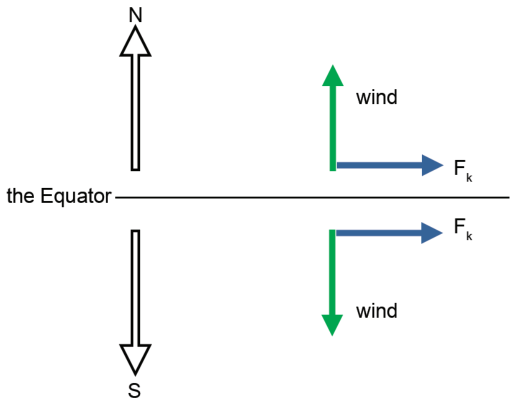

Figure 5. Coriolis force in the northern hemisphere and in the southern hemisphere

The given formula explains the following:

Coriolis force acts on the moving objects

Magnitude of Coriolis force is proportional to the velocity of the object

when the latitude increases the intensity of Coriolis force also increases

Due to the Coriolis force, there is the turning of the winds to the right in the northern hemisphere and to the left in the southern hemisphere. The impact of Coriolis force ranges from several hundred kilometres to planetary distances. The intensity of Coriolis force equals zero at the Equator but reaches the highest values at poles, which is different from the intensity of centrifugal force which is the highest at the Equator but equals zero at poles.

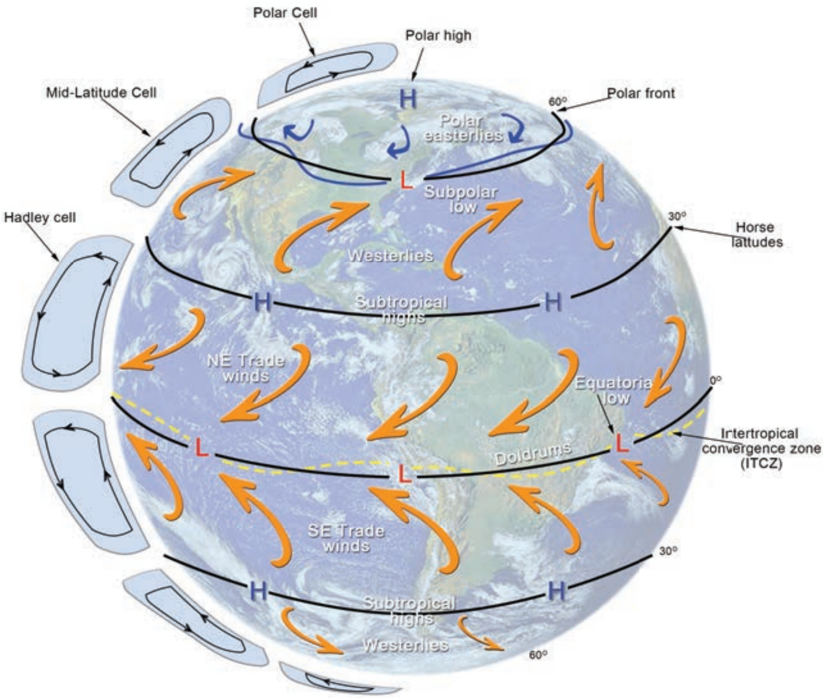

Figure 6. Idealised distribution of the surface pressure and constant winds

YEAR

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Teaching topic:

THERMODYNAMICS

Teaching units:

1. Changes of internal energy without the work done
2. Thermal balance
3. Specific thermal capacity of substance and molar thermal capacity

Thermodynamic phenomena and thermal characteristics of substance

The branch of physics that deals with thermal phenomena on macro level and thermal features of substances is called thermodynamics. Thermodynamic processes work and are based on the principles of thermodynamics.

The most important thermal phenomena are the heat transfer, i.e. change of internal energy without any work applied by means of the mechanisms of conducting, circulating and radiating (conduction, convection, and radiation, respectively) and establishing the thermal balance. Physical quantity that describes behaviour of the objects under the influence of thermal energy, such as specific thermal capacity of substance, molar thermal capacity and their relations, are used for thermal features of substances.

Conduction, convection and radiation. Internal energy of gasses is equal to the total mean kinetic energy of gas molecules because due to weak intermolecular forces the potential energy of mutual molecular interaction can be neglected. The change of internal energy is performed by the exchange of the amount of gas heat and the surroundings. The mechanisms of the internal energy change without the work done are conduction (conducting), convection (circulation) and radiation (radiating).

Conduction is the characteristic of solids. When heat, for instance, is transferred to an object its molecules oscillate with higher amplitude because their kinetic energy increases and owing to intermolecular forces, the energy is transferred to neighbouring molecules and so on in that order. Molecules are not moved by themselves.

Convection is the characteristic of the heat transfer in liquids and gases. First, the layers of liquid or gas that are the closest to the heat source are heated, their density decreases, they move upwards, then denser, colder layers come into their position and the circulation starts. Different from the mechanism of conduction, the molecules of liquids or gases move and "carry" their own energy.

Radiation occurs when heat radiation is transferred through substances in the form of particles of electro-magnetic radiation – photons.

Thermal features of objects are described by physical quantity such as specific heat capacity of substance (c) and molar heat capacity (C). Numerical values of these quantities indicate whether the substance is a good or bad heat conductor.

Specific heat capacity is the characteristic of substance that shows the amount of heat that needs to be added to or removed from the unit of the substance in order to change its temperature for one unit value (1K or 1^0C):

$$c = \frac{Q}{m \triangle T}$$

Molar heat capacity is usually used for gases and indicates the amount of heat that needs to be added to or removed from one molecule of gas in order to change its temperature for one unit value (1K or 1^0C).

$$c = \frac{Q}{n \triangle T}$$

Thermodynamic or heat balance is established after the heat is transferred between the parts of thermodynamic system, internally and with the surroundings. After the thermodynamic balance has been achieved, all parts of the system and the surrounding are at the same temperature.

Temperature of the soil and the air

The aforementioned phenomena have crucial impact on vegetation. The surroundings in which a plant grows and undergoes its life cycle consists of soil and atmosphere. By means of conduction process plants exchange thermal energy with the soil and by means of convection process with the air.

Apart from defining standard thermodynamic quantities, the quantities that are characteristics of the application of the laws on thermodynamics on the vegetation are also defined: *thermal conductivity* K_h and *thermal diffusivity* D_h.

Thermal conductivity indicates the ability of a substance to conduct heat. It is defined as energy that is transferred per unit time through the part of the volume of unit area and unit height at temperature difference of 1K of the opposite sides.

Thermal diffusivity is the measure of heat inertia and it indicates the ability of a substance to conduct heat with reference to the ability of a substance to save energy. It is defined as the ratio of thermal conductivity and the product of density and specific heat capacity. These thermal properties of certain substances, for instance, soil, depend on the moisture since water has significantly larger specific heat capacity from other components of soil.

Table 3.1. gives the typical values of certain thermal quantities for certain constituent parts of soil and geological formations. For example, it is visible that sandy soil has the highest thermal conductivity.

Typical values of density,r, specific thermal capacity, C_h, thermal conductivity, K_h and thermal diffusivity, D_h, of certain components of soil and geological formations.

	ρ (10^3 kg m^{-3})	C_h (10^3 J kg^{-1} K^{-1})	K_b (J m^{-1} s^{-1} K^{-1})	D_h (10^{-6} m^2 s^{-1})
Air	0,00116	1,007	0,025	21,4
Quartz	2,65	0,84	8,8	3,95
Humus	1,4	1,9	0,25	0,094
Water	1,00	4,22	0,57	0,14
Ice	0,91	2,11	2,2	1,15

Heating and cooling of soil

Heating and cooling of soil is the result of energetic balance of the Earth's surface. Since electromagnetic radiation can not penetrate through soil, a portion of energy left at the surface after reflection becomes transformed into heat. Intensive heating of the surface soil layer and energy conduction govern the soil temperature profile. Absorption and conduction of heat energy are greatly affected by surface and soil characteristics such as *colour* and *roughness, specific thermal capacity and thermal conductivity*.

- ✓ Colour and roughness: A dark surface has high absorptivity, which reduces its albedo. A rough surface has a lower albedo than a smooth surface of the same soil due to intensive absorption of radiation caused by multiple reflections and to absorption of radiation on elements of roughness.
- ✓ *Specific heat capacity:* In comparison to water, soil has a lower heat capacity, resulting in faster heating and cooling of the soil surface. However, moistening of the soil increases its heat capacity.
- ✓ *Thermal conductivity:* Soil wetness affects thermal conductivity. Energy transfer from the soil surface to deep soil layers, and vice versa, is more efficient in wet than in dry soils.

Surface temperature, or "skin" temperature, is a key factor affecting the temperature of the thin overlying part of the atmosphere, which is responsible for dew and frost formation. Subsurface soil temperature depends on heating of the surface layer and the soil characteristics affecting energy transfer. Heating and soil characteristics both change during the day and year and produce the diurnal and annual cycles of the soil temperature profile.

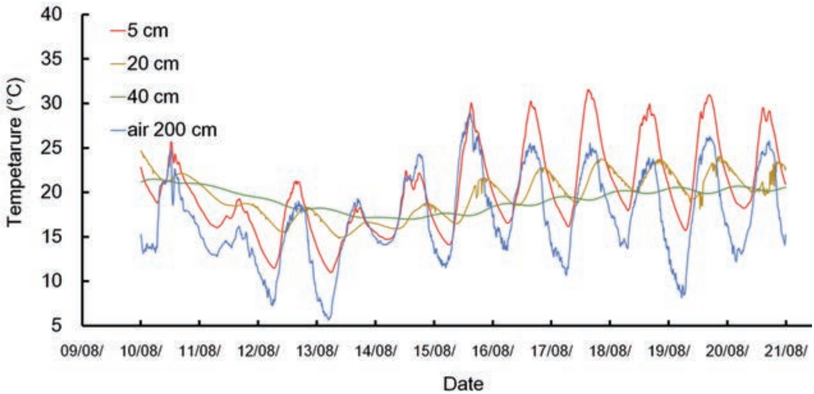

Figure 1. Daily variation in soil (grass cover) and air temperature during the summer 2016, Goggendorf, Austria (Source: BOKU-Met).

During the day, the surface area of soil attains its maximum temperature approximately one hour after maximum solar radiation. On the other hand, the soil surface reaches its minimum temperature just before the sunrise. However, a time lag in the occurrence of maximum and minimum soil temperatures increases with depth. A time lag is actually the time required for surface layer heating and energy transfer through the soil column, which greatly depends on the heat capacity of the soil. Daily variation in soil temperature decreases with depth until it reaches a constant temperature level. On average, this level is reached at the depth of 1 m, although it may be dependent on the soil type and wetness, season and latitude.

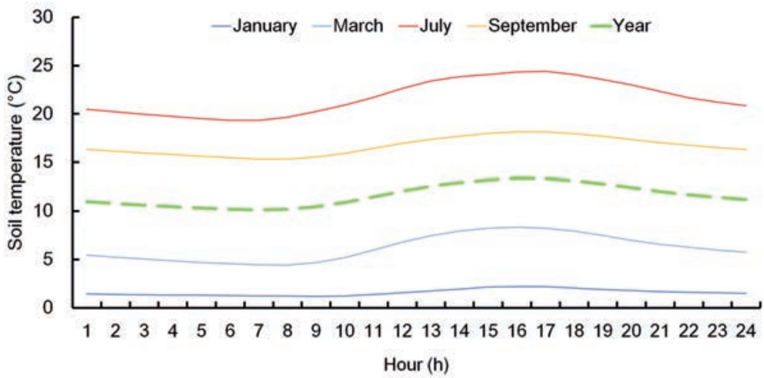

Figure 2. Seasonal variation in the daily course of soil temperature at the depth of 10 cm in Ridjica (Serbia) (2013-2017). (Source: PIS Vojvodina, Serbia)

The daily course of soil temperature has a seasonal character, which is particularly visible at the surface layer. In winter, surface heating during the day is lower than in summer, due to less daylight and the lower intensity of solar radiation. It produces a smaller daily variation in soil temperature during the winter and a greater variation during the summer. Additionally, daily variation in temperature increases at lower latitudes, due to the intensive diurnal heating and nocturnal cooling that take place as one nears the Equator. Consequently, at low latitudes the depth at which constant daytime soil temperature is achieved is greater during the summer.

Soil temperature in the Northern Hemisphere reaches its annual minimum in January and its maximum in July. During the year, soil temperature variation decrease with depth until the level of constant soil temperature is reached. Annual temperature changes are the cumulative effect of daily temperature fluctuations and thus they penetrate much deeper into the soil than daily temperature variations.

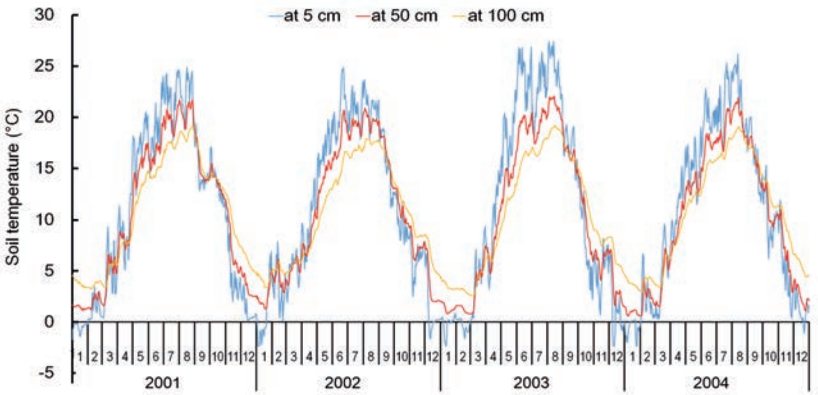

Figure 3. Annual variation in temperature for grass covered soil during 2001-2004 in Doksany, the Czech Republic. (Source: Mendel University, Brno)

Heating and cooling processes of the air

Mechanisms that regulate heating and cooling of air are the following:

- ✓ *conduction* – the process of energy exchange effected by molecules between
  the soil surface and the atmosphere with a thin air layer (usually only a few mm);
- ✓ *turbulent mixing* – the exchange of energy (and substance) between the soil surface and the atmosphere and between different atmospheric layers by turbulent eddies within an atmospheric boundary layer. The thickness of this layer varies during the day, with a typical value of 1 km;
- ✓ *convection* – the rising of warmer and the descending of colder air,
- ✓ *radiation* – energy transfer by electromagnetic waves, which in the case of atmosphere is dominated by the absorption of the solar and terrestrial radiation. The content of the atmosphere can significantly affect atmospheric warming by radiation;
- ✓ *advection* – in the atmosphere, this is energy transfer governed by wind blowing from one region to another and bringing air of a different temperature;

- ✓ *evaporation and condensation* – phase changes of water in the atmosphere followed by the release or engagement of energy in the form of latent heat flux. This heat transfer is an important source and sink of energy for the atmosphere (23% solar constant).

During the day, at the height of a few metres above the ground, the air temperature reaches its maximum 2-3 hours after the time of maximum solar radiation and 1-2 hours after that of the maximum soil surface temperature. This lag in time is the consequence of the fact that certain time is required for the soil to be heated by the solar radiation and, later on for the air to be heated by terrestrial radiation. Daily variation in air temperature depends on: latitude (higher if closer to the Equator), season (highest in summer), land use (highest in the case of sandy bare soil or rock), landscape (higher in lowlands), altitude (higher at lower elevations), cloudiness (higher under a clear sky) and vegetation cover (higher in the case of bare soil). However, daily variation in air temperature is lower above a water surface (never exceeding 1.7 °C) than above the ground.

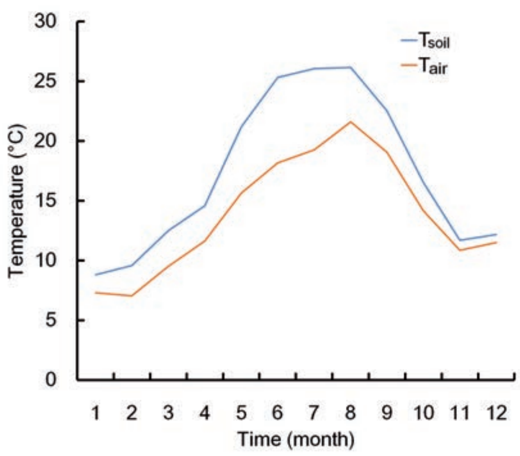

Figure 4. Average annual variation in air and soil temperatures for the period 2005-2011 on Elba (Italy). (Source: Regional Hydrometeorological Service of Tuscany)

The annual cycle of air temperature follows annual cycle of the underlying surface temperature (Fig. 3.5). The highest annual variation in maritime air is up to 20 °C, while for places deeper inland it reaches 60 °C. Annual variation in air temperature depends on: latitude (lower if closer to the Equator), land use (highest in the case of sandy bare soil or rock), altitude (higher at lower elevations), cloudiness (higher under a clear sky) and vegetation cover (higher in the case of soil without vegetation).

Proximity of larger water areas may significantly impact daily and annual air temperature variation. Due to the higher heat capacity of water, oceans accumulate 16 times more energy than landmasses over the year. Therefore, bodies of water heat more slowly in spring and summer and cool down more slowly during autumn and winter. During the winter, air temperature above the water and above the land regions affected by bodies of water is always warmer than air temperature above the landmass father inland. On the other hand, air temperature above water and areas under the influence of water is cooler in summer, with much smaller daily and annual variations.

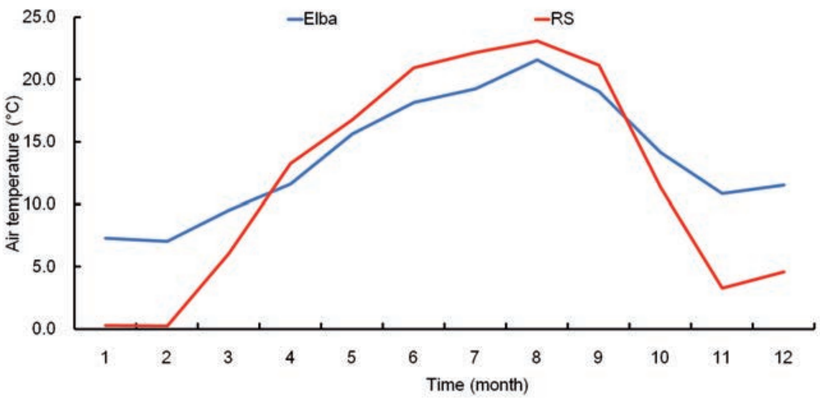

Figure 5. Annual variation of monthly air temperatures during 2011 on Elba (Italy) and Rimski Šančevi (Serbia). (Source: Regional Hydrometeorological Service of Tuscany and Republic Hydrometeorological Service of Serbia)

2

Teaching topic:

MOLECULAR THEORY OF SOLIDS AND LIQUIDS AND PHASE TRANSITIONS

Teaching units:

1. Atmospheric evaporation and condensation
2. Saturated water vapour

Evaporation

Evaporation is the phase transition of the substance from liquid into gas matter. It occurs at all temperatures (evaporation from the surface) and at boiling point (bulk boiling).

Evaporation from the surface is explained from the point of view of molecular physics.

The molecules in the surface layer of a liquid are more loosely bound because they are not surrounded from all sides by other liquid molecules. Those molecules have more kinetic energy and can more easily separate from the liquid and leave it. The process in which molecules leave the liquid is called evaporation.

Evaporation speed is equal to the number of molecules that per unit time and per unit area transit from liquid into gas phase. The speed or intensity of surface evaporation depends on temperature (at higher temperatures evaporation process is faster since molecules have more kinetic energy), type of liquid (molecular forces are stronger, evaporation speed is smaller since molecules cannot overcome intermolecular forces), size of free surface areas of liquid (if the free surface is larger, the evaporation is faster because larger numbers of molecules leave the surface of the liquid per unit time) and water vapour pressure on the free surface of liquid (the stronger the pressure, the smaller evaporation speed).

Because the molecules with the strongest kinetic energy (the fastest molecules) leave the liquid during the evaporation process, mean kinetic energy of liquid molecules decreases, i.e. the temperature of the liquid decreases – the liquid is cooling down.

Condensation

Condensation is the process of substance transfer from gaseous into liquid state.

The molecules move chaotically in water vapour above the liquid. During that motion some molecules approach to the surface close enough so that molecules from the surface layer can act upon them by molecular forces and attract them into the liquid.

The condensation speed is equal to the number of molecules that transfer from the gas into liquid phase per unit time and per unit area. If the water vapour concentration is higher, the condensation process will be conducted faster. The condensation speed depends on the type of substance and water vapour temperature. However, temperature has less impact on condensation than on evaporation. The process of condensation is accompanied by the process of heat release.

Saturated water vapour

The term saturated water vapour refers to the water vapour which is in thermodynamic equilibrium with liquid. In that case the number of molecules that leave the liquid in the evaporation process equals the number of molecules which return to the liquid per unit time. In case such a system would be left on its own, none of these would change: temperature, pressure and amount of water vapour and liquid.

The state of thermodynamic equilibrium at certain temperature is achievable for only one value of the pressure. The pressure is called saturated water vapour pressure. Its value depends on temperature.

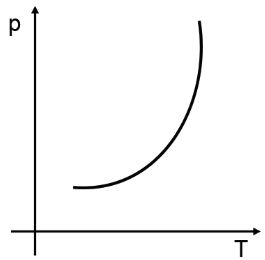

Figure 1. Dependence of saturated water vapour pressure on temperature

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Air humidity

Water that evaporates into air adds humidity into it. At certain temperature, certain air volume may contain maximum amount of water vapour and in that case the air is saturated. By decreasing the temperature to a certain value, the air becomes supersaturated and the excess water vapour, below the dew point, is condensed into droplets of water or sublimes into ice crystals.

The diagram of phase transition water-water vapour shows at which values of pressure and temperature water exists in liquid and gas states and at which values there is equilibrium of both phases.

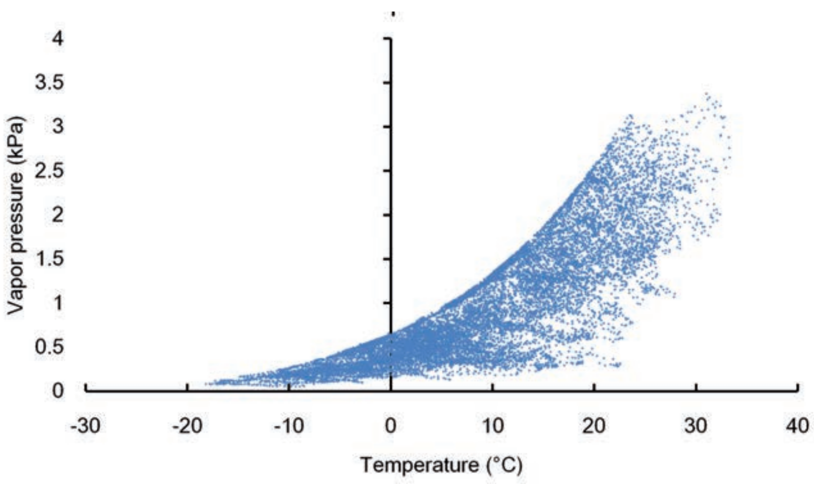

Figure 2. Measured values of water vapour pressure at different temperatures

The graph shows that the phase transition can be conducted, not only by means of temperature change which is known from everyday life, but also by means of pressure change. The temperature at which the air is saturated is called dew point. Maximum partial pressure and maximum amount of water vapour in the air depend merely on temperature and are always the same for certain temperature. At higher temperature, maximum pressure and maximum amount of water vapour in the air are higher.

Air humidity is the consequence of the water vapour cycle in the atmosphere. In numerous subsequent processes, water transits from ice phase into liquid phase, from liquid phase into water vapour and vice versa. The role of water and atmospheric humidity is an important factor in the life cycle of plants and vice versa.

Processes that follow the water cycle

Water's phase changes (liquid, solid or gas) depend on intermolecular forces which tend to group molecules and their kinetic energy which gives the molecules the possibility to split and it is proportional to temperature. If mean kinetic energy is higher than work applied to overcome intermolecular forces, water will be in the form of water vapour. Otherwise, water will exist in the form of liquid or ice.

Evaporation. The process in which molecules escape from the surface of liquid (water) is conducted at all temperatures. Intensity, i.e. velocity of this process depends on water temperature and on vapour pressure deficit (VPD, the ability of the surrounding air to hold additional molecules of water). It may be concluded that there will be no evaporation when VPD equals zero (saturated air), but it is not completely true. Namely, in that case evaporation also occurs when molecules with small kinetic energy, which are located close to the surface of liquid, are "captured" by the liquid molecules. That is the example of the process of *condensation*. Condensation and evaporation are the processes that occur at the same time, but what distinguishes one from the other is whether there is the higher number of molecules which escape from or return to the liquid. The possibility of molecular collision and capture of other molecules of gas increases with the decrease of mean kinetic energy for certain volume and at constant pressure. Since the temperature drops in that case, it explains why maximum partial pressure of vapour depends exclusively on the temperature and drops when temperature drops. On the contrary, at constant temperature, the increase of atmospheric pressure decreases mean free escape path of molecules and increases the intensity of condensation (the greater chance of colliding). The same effect is achieved when under constant atmospheric pressure and constant temperature the amount of water vapour increases in the air and such higher concentration also increases the chances of colliding.

Melting. Melting is a physical process in which by application of thermal energy the intensity of intermolecular forces decreases to the level at which molecules distance to the point which is the property of the liquid phase. The reverse process is *solidification*, and the direct transition from solid phase into the gas phase is called *sublimation*.

Atmospheric evaporation and condensation

The surface of the Earth is the constant source and sink of energy and humidity from atmosphere.

Evaporation from the bare soil is impacted not only by the same meteorological conditions as the evaporation from the open water surface (temperature, VPD), but also by the characteristics of soil, such as the type and structure of soil, humidity of soil, and ground water presence.

Vegetation releases water into atmosphere as a result of two processes: physical process of evaporation from the surface of plants and physiological process of transpiration, i.e. diffusion of vapour from plants trough stomata. The term used for these two processed is *evapotranspiration.*

Condensation, followed by the release of latent heat, represents a powerful source of energy for the atmosphere. For instance, driving force of tornado originates from the energy released by water condensation. Condensation occurs in the following cases:

a) when moist air flows over the colder surface

b) when air temperature decreases due to intensive irradiation of an underlying
surface

c) when mixing of warm and cold air masses occurs

d) when air is forced upward greatly reducing its temperature due to pressure decrease, while keeping the initial amount of unsaturated water vapour. At a certain point, air will cool enough to reach the dew point temperature for a given amount of water vapour.

Fog is created as a product of condensation process in the atmospheric layer immediately above the ground. Depending on the process which leads to condensation and the difference of dew point and air temperature, different types of fog are produced: advective fog, radiation fog, frontal fog and upslope fog.

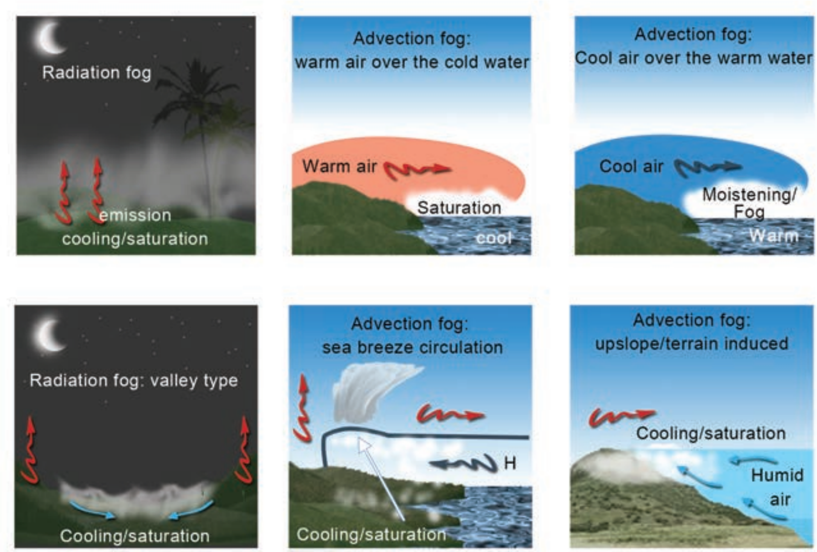

Figure 3. Mechanisms of forming different types of fog in the atmosphere

Teaching topic:

THERMODYNAMICS

Teaching units:

1. Thermodynamic balance
2. Principles of thermodynamics
3. Adiabatic processes

Thermodynamic balance and principles of thermodynamics

Thermodynamic or heat balance is achieved after the exchange of amounts of heat occurs between the parts of the thermodynamic system, internally and with the surroundings. After the thermodynamic balance is achieved all parts of the system and the surroundings are at the same temperature. The processes of exchange are conducted in concordance with the principles (laws) of thermodynamics.

The first principle of thermodynamics:

Amount of heat (Q) which the system exchanges during a process with the surrounding partly is applied to work (A) and partly it is spent to change of inner energy (ΔU).

$$Q=A+\Delta U$$

The second principle of thermodynamics defines the direction of thermodynamic processes and it states:

A thermodynamic transformation of which the only result is to transfer heat from a body at a lower temperature to a body at a higher temperature is impossible. (*Clausius postulate*).

That is to say, spontaneous heat transfer is only possible from higher temperature body to lower temperature body.

Clouds and precipitation-introduction

Whether they are as thin as spiders' net, high-positioned in the skies, lead-coloured or they seem so low-positioned that they can be reached by hand, the clouds are the most impressive visible products of water vapour condensation as well as other processes that define their type, content, height and size. The presence of clouds impacts the energetic balance of the atmosphere and the Earth surface. Snow white cumulus clouds cause multiple reflection of the Sun radiation, thus creating higher intensity of the Sun radiation when compared to the upper layer of the atmosphere.

Precipitation is a result of water vapour condensation that occurs in the atmosphere and then its products arrive to the surface of the Earth in either solid or liquid state. Prior to the detailed analysis of cloud formation and precipitation, it is important to explain adiabatic processes for air and atmospheric stability.

Adiabatic processes and atmospheric stability

In order to explain why the air is rising under certain circumstances and sinking under other circumstances, it is essential to introduce atmospheric adiabatic processes and explain the concepts of air parcels and atmospheric stability.

An air parcel refers to a volume of air which has such properties that it can be used to explain the behaviour of the surrounding air. It is small enough to have unique properties in its volume, maintaining all the basic thermodynamic and dynamic properties of atmospheric air which it represents.

Adiabatic process is the process that occurs without matter transfer (energy and substance) between a system and its surroundings. In concordance with the first principle of thermodynamics, the energy that is transferred to the thermodynamic system (Q) may be spent on the changes of energy in the internal system (DU), i.e. temperature changes and work applied by the system (A), such as expansion or compression.

In adiabatic processes ($Q = 0$ and $A = -\Delta U$) there is no energy transfer between the system and surroundings. In case any work is done, it is done on the internal energy of the system, which results in temperature decrease.

Regarding the definition of adiabatic processes, questions arise whether an air parcel can be considered an adiabatic system and whether the rising of an air parcel can be considered an adiabatic process. The answer is positive: even if it is not isolated from the surrounding air, but moves fast enough, an air parcel may be lifted without energy transfer with the surroundings.

What is the manifestation of this phenomenon in the atmosphere? We will assume that, due to the interaction of air parcels with colder and denser surrounding air, the force of thrust occurs. Thrust force acts upon an air parcel to rise until it is warmer and less dense compared to the surroundings. As it is lifted, an air parcel is exposed to a smaller atmospheric pressure[1] which leads to the increase of its volume and temperature decrease. This phenomenon is known in literature as *adiabatic cooling of rising air*.

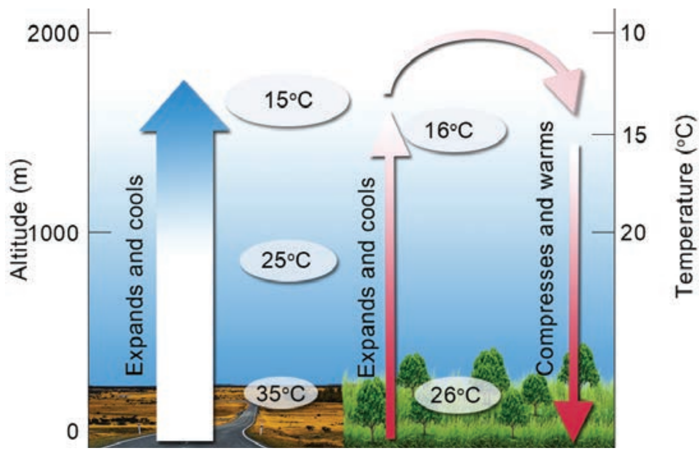

Figure 1. Rising of air in instable and stable atmosphere.

[1] Pressure in the atmosphere decreases when the altitude increases, due to the decrease of air density when the altitude increases and shortening of the air column which creates atmospheric pressure at the observed point.

At lower temperatures, the initial amount of water vapour will produce increased relative humidity[2] and an air parcel will become more and more saturated as it is lifted. At all points up to the point when relative humidity of an air parcel reaches 100%, the rising of an air parcel is called *dry adiabatic* process, whereas the temperature decrease, which occurs with altitude change, is called *dry adiabatic temperature gradient*. If an air parcel cools down to the dew point temperature, condensation process occurs and the released latent heat of condensation heats the air parcel by reducing its temperature gradient. Such rising is called *moist adiabatic process*. Specifically, *moist adiabatic gradient of temperature decrease* is always smaller than the dry adiabatic, but largely dependent on the initial amount of water vapour in the air parcel.

Static stability of any physical system, including an air parcel, is defined with reference to state in which either acting forces are not present or acting forces are balanced. The balance of forces may be stable, which refers to the state in which the object tends to return to its initial state after the forces cease to act, or instable, when a small disorder produces significant changes, so that the return to the previous state is impossible.

If the temperature gradient of the surrounding air is lower than dry adiabatic temperature gradient, then the air parcel that is forced to lift up (due to the relief or the thrust force) will become colder and denser than the surrounding air and tend to return to its initial position. That type of the *atmosphere* is *absolutely stable*. The cooling process of the surface air layer occurs most frequently due to the advection of cold air or intensive night cooling process, which mainly produce the most stable air immediately before the sunrise, when the temperature reaches its minimum. Because stable atmosphere strongly resists to any vertical movement, it thus allows the fog to remain near the surface of the soil in early morning hours. Heating of the surface layer of air is the result

[2] This situation is the consequence of the fact that maximum water vapour pressure decreases with temperature decrease. Thus, the same amount of water vapour will be closer to the saturated state with temperature decrease. Formal explanation follows from the mathematical formulation of relative humidity, r (r = pressure of water vapour/maximum water vapour pressure*100%) which shows that if maximum pressure decreases, relative humidity increases at constant pressure of water vapour.

of warm advection or slow air cooling process during the night which may lead to slowing down the whole cooling process. Under stable conditions, the inversion acts as atmospheric ceiling, preventing the vertical transfer and keeping all the products of condensation and all the polluting matter near the surface of the Earth.

Figure 2. Fog retention in stable atmosphere

If the temperature gradient of the surrounding air is higher than the dry adiabatic temperature gradient, unsaturated air parcel that lifts up will cool down more slowly than its surroundings, i.e. it will always be warmer and less dense than the surrounding air. Hence, when an air parcel once starts to rise, it will continue the vertical movement in that *absolutely instable atmosphere* under the impact of the thrust force. Atmospheric instability increases with the increase of the temperature gradient of the surrounding air what is a common phenomenon when the air at surface is being heated or the air above it is cooling. Temperature of the surface air layer increases as a result of warm advection or daily heating of the Earth's surface due to the sun radiation, which causes intensive vertical mixing in the atmosphere. Consequently, atmospheric stability changes from stable to instable during the day.

Stable atmosphere which contains water vapour, especially in the morning when a dry day follows, is also an important source of humidity for plants and animals. However, in case of frost, stability of the atmosphere, which is related to inversion, creates frost damage, intensity of which depends on the inversion intensity and stability level (which define the duration of frost) and on the point to which temperature dropped below 0°C (which defines intensity of frost).

Instable atmosphere enhances vertical heat and water vapour transfer from the soil surface and vegetation into the atmosphere, which significantly impacts the energy and water balance on the surface. It may increase the intensity of evapotranspiration and gas transfer between plants and surface layer of the atmosphere, which simultaneously increases intensity of all physiological processes related to them.

Clouds and formation of clouds

Clouds are visible products of condensation and sublimation (direct transfer of substance from solid into gas phase) of water vapour in the atmosphere which may be formed either near the soil or at high altitudes; they may be thin, but with high vertical size or as high as the top of planetary boundary layer of the atmosphere, or the size of a smaller corn field in horizontal size.

Water vapour condensation and cloud formation in the atmosphere mainly occur when: a) warm air rises due to convection process, b) warm air is forced to rise while approaching a mountain or an atmospheric front, and c) warmer and colder air collide and mix in the atmosphere. Whether the clouds are formed slowly in stable atmosphere or by fast convection in instable atmosphere defines their appearance and the precipitation type that forms within them.

Layered (stratus) clouds are formed under the conditions of strong static stability and slow formation of layers of large horizontal size. Convective clouds are usually the result of heating process in the atmosphere and convective rise of humid air from the Earth towards the top layer of the atmosphere or fast movement of cold front which causes the rising of the air on the front. Combination of these two types of clouds is possible if, for instance, convective elements appear in layered clouds due to local instability. Contrary to the large horizontal size of layered clouds, convective clouds are characterised with vertical size. The more intensive convection and more water vapour within the cloud, the larger the vertical size of the cloud.

Since the clouds constantly change, there are various forms of them which demand a proper classification. The first classification of clouds was made by a British pharmacist and amateur meteorologist Luke Howard who published his "Essay on cloud modification" in 1803. His classification was based on ten classes of clouds; it was later on modified and accepted by the World Meteorological Organisation (WMO) as the basis for ten major groups, or types of clouds: Cirrus (Ci), Cirrostratus (Cs), Cirrocumulus (Cc), Cumulonimbus (Cb), Altocumulus (Ac), Altostratus (As), Nimbostratus (Ns), Stratocumulus (Sc), Stratus (St) and Cumulus (Cu). Further classifications are based on the part of atmosphere (troposphere), i.e. the altitude at which low level, mid level and high level clouds usually form.

The names of clouds are usually derived from Latin words that describe their form. In order to describe the characteristics of clouds more precisely, the prefix *alto-* is used for high level clouds and the prefix *nimbo-* is used for rainy clouds.

The content of clouds depends on altitude, position and mechanism of their formation; it is characterised by different content of ice crystals, snow and rain drops of various sizes as well as various combinations of all these elements. According to the temperature and content, clouds are defined as either *warm* or *cold*. Only if the temperature of the total volume of the cloud is above 0°C and the cloud consists of liquid droplets, it may be considered warm – such clouds are the characteristic of tropical and subtropical areas. However, if the top of the cloud reaches the altitudes at which temperatures are far below 0°C, its content is predetermined by a mixture of ice crystals and liquid droplets. Such formation, typical for middle and high latitudes is called a cold cloud.

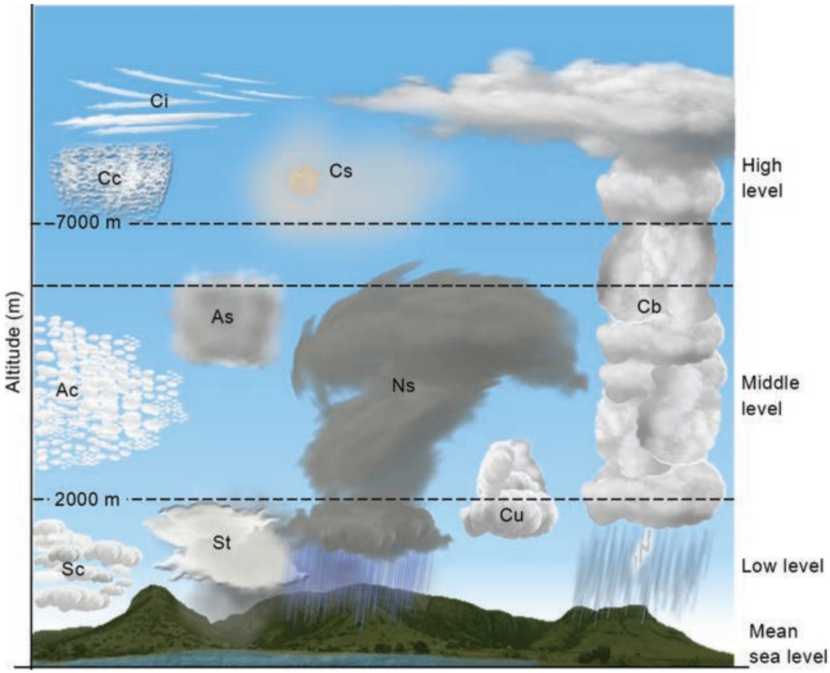

Figure 5. Classification of clouds: type, level, height, and symbol

2

Teaching topic:

ELECTROSTATICS AND ELECTRIC CURRENT

Teaching units:

1. Charging of objects. Electrostatic influence
2. Electrical field
3. Capacitor
4. Electrical conductivity of gases

Atmospheric electricity

Various electric phenomena occur in the atmosphere with the dominance of electric discharge in the atmosphere. Electrical discharge is accompanied with sound effects (thunder) and light effects (lightning).

Lightning is especially important because in one period of life development on the Earth lightning was the source of molecules out of which life might have evolved. In their discharging channel and around it, lightning creates certain chemical elements which do not exist in the atmosphere or exist in insufficient quantity. One of the examples is nitrogen which is essential for plants in production processes. Lightning system has a function of maintaining the charge system in the atmosphere which is necessary for nice weather conditions.

Lightning has harmful effect on living world, telecommunication and electro energetic systems, buildings, etc.

Electric currents flow vertically through the Earth's atmosphere, which means that there is electric field in the atmosphere and the atmosphere has the property of electrical conductibility. Electrical conductibility of air, which shows dielectric properties, is achieved by ionisation of air molecules by cosmic rays during which electrical conductibility increases with the increase of altitude.

Positive and negative ions and free electrons are formed in the atmosphere during the ionisation process of atoms and molecules of the air. They may be further combined with other molecules, particles of dust, rain drops, snow and ice crystals and other elements of clouds and form an electric charge and thus the Earth's atmosphere has the property of electro conductivity.

Air gets the property of electro conductivity at 50km altitude which is considered lower limit of ionosphere. Between ionosphere and the Earth's surface there is the difference of potential. The Earth's surface is negatively charged and lower limit of the ionosphere is positively charged. The area in which the difference of potentials dominates acts as a capacitor.

Lighting occurrence

Lightning occurs when large enough potential difference, i.e. strong enough electric field, is achieved between certain parts of the atmosphere, due to the accumulation of electric charge. At that point the air "breakthrough" occurs, i.e. the air becomes electrically conductive. Charged particles move from higher towards lower potential while ionising and warming the air. Those processes are accompanied with light emission, i.e. lightning occurrence.

Lightning is most frequently "initiated" inside a thundercloud cumulonimbus where positive and negative charges split and cumulate due to very intense convective movements.

Lightning travels towards the surface of the Earth in steps, pauses and continues towards the ground (Figure 1).

Figure 1. Lightning "initiation" in thunderclouds and its path towards the ground

Lightning can occur:

- within a cloud
- between a cloud and the air
- between two clouds
- between a cloud and the ground

Electric charge in the atmosphere

Electric charge of clouds is the consequence of global water circulation on the Earth by means of condensation and evaporation. During the process of vaporisation water evaporates from the Earth's surface and elevates into higher layers of the atmosphere. Because the temperature decreases as the altitude increases, condensation of water vapour occurs, for example on dust particles, and it falls to the Earth surface in the form of rain or snow, depending on the temperature. When humidity amasses in the atmosphere, the clouds are formed carrying millions droplets of water or ice crystals. Besides condensation on particles in the air, there is also condensation on water drops and ice crystalline, which form the thunderclouds, because they constantly collide with them during convective movements. During collision process electrons escape from water vapour and form negative electric charge in the lower part of the cloud, and the molecules of water vapour continue their movement towards the upper part of the cloud where positive electric charge is formed and the first condition for electric discharge is achieved. Creation of potential difference is accelerated by air convection process (air currents).

The Earth's surface and lower boundary of ionosphere may be observed in a simplified manner as the coatings of a large capacitor where the Earth's surface is a negative panel, and the lower side of ionosphere is a positive panel. This "capacitor" discharges in the areas of nice weather and charges in the areas of thunder activities.

Figure 2 shows the scheme of a thundercloud serving as a battery for maintenance of global electrostatic field and electric circuit in the atmosphere.

Electric discharge in a thundercloud in the atmosphere

Electrical charges in a thundercloud are distributed on the elements of a cloud (cores of condensation and sublimation, rain drops, ice particles and snow crystals). The areas inside a cloud with prevailing charges of the same type are made of positive or negative cells within the clouds. Figure 2 represents the scheme of a cloud with two oppositely charged cells. Charged particles and electricity cells of the same type within the cloud are mutually separated by neutral air, which is a bad conductor of electricity. Turbulence pulls and pushes certain particles and areas of the same charge within a cloud, which causes changes in the strength of the electric field. When the current value of the field reaches critical value of the strength (> 1 MV/m), impact ionisation occurs and electric spark is created, i.e. occurrence of lightning.

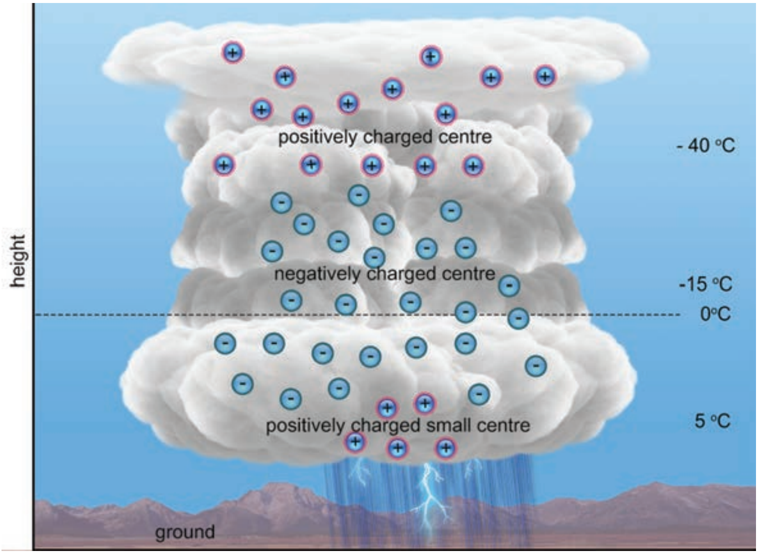

Figure 2. Example of the electric charge distribution in a thundercloud cumulonimbus incus

If the clouds are more electrically charged, the electric field is stronger. At some point it becomes so strong that the electrons at the surface of the Earth will try to “withdraw”, i.e. try to insert themselves deeper into the soil. As the electrons “withdraw” into the inner parts of ground, the ground becomes more and more positively charged. The storm leads to sudden creation of an electric filed within a cloud and between the cloud and the ground. When the excess charge is created, i.e. when electric field becomes strong enough it will force the surrounding air to “burst”. This “bursting” of air is the process of separating positive and negative particles in the air and it is called ionisation. Ionised air has much higher electrical conductivity. Since the air is not equally ionised in all areas, in the areas where ionisation is more intensive the “paths” are created – the trails for the lightning to “jump over” easily. For lightning to be created, it is necessary that the electric path reaches the ground and finds the “grounding” - point or object at which it will stop. When this happens, the lightning will flash. The light we see on that occasion is the result of electric discharge between the cloud and the ground which follows the already crated electric path.

There is the difference between thermal and mechanic activity of the lightning and the thunder. When electric current passes through a highly resistant device or object, heat is developed. If the object has cracks filled with, e.g. water, high pressure vapour is developed and it can cause decomposition of the object (demolition of a wall, chimney, splitting of trees or wooden columns and similar due to a thunder strike). When thunder, i.e. its lightning, strikes into flammable material it causes fire. The current caused by the lightning ”flows” down the smooth and wet bark of beech tree, but not through the outer rough bark of oak tree; instead, it passes under the tree bark through the tree rings rich in capillaries. After the lightning or flash we can hear the thunder due to a high heating and expansion of air within the lightning channel (temperature reaches the value of 10^4 K and above).

After an abrupt expansion, cooling process of the surroundings and compression occur and then compression or sound waves are created according to the same mechanism such as a cannon rumble.

There is the difference between the sound of thunder and cannon rumble. Sound wave of the cannon shot spreads in concentric circles from its source and it is heard in one rumble. Thunder is caused by sound waves crated along the channel of the lightning several kilometres long (cloud to ground, within a cloud or between several clouds).

Return current travels along the channel at the speed approximate to the speed of light (a bit slower) and the whole channel is practically lit at the same time.

Types of lightning

Branched lightning

It occurs at electric discharge in the direction cloud – ground as in Figure 3. The leading paths are winding and branched (side lightning), but only one channel or a pair of channels (the brightest ones) reach the ground.

Figure 3. Branched lightning

Ribbon lightning

A shiny ribbon is observed as stretching from the cloud base to the ground (Figure 4). It is created by consecutive electric discharges, with simultaneous side movement of ionised channel as a result of strong wind whose direction is almost normal to the direction of the lightning channel.

Figure 4. Ribbon lightning

Multiple lightning

Figure 5. Lightning from two different clouds

Lightning path or ionised channel

It is the ionised channel along which electric discharge occurs. The lightning path is interrupted and poorly glittering. The parts that are stronger enlightened remain visible for a longer period. Since there is a very short interval between certain phases, the lightning path is hardly visible to the naked eye. By the application of the motion picture, certain phases of lightning occurrence may become visible (Figure 6).

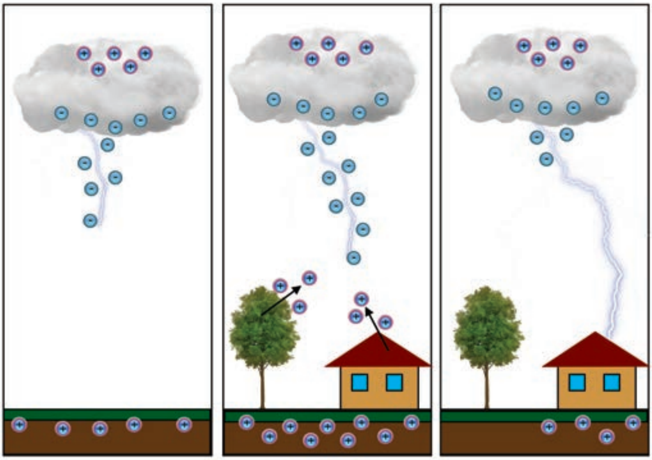

Figure 6. Certain phases of lightning.

Atmospheric discharge

It is the electric discharge from clouds which does not reach the ground (Figure 9 and Figure 10). Ionised channel advances horizontally and may reach the length of several dozens of kilometres. Occasionally, such channel re-enters the same cloud or another neighbouring thundercloud.

Figure 7. *Figure 8.*

Electric discharge from the clouds in the atmosphere

Electric discharge from the ground towards the cloud

In this case the leading path and lightning starts from the ground towards the thundercloud when the thundercloud is positioned above a prominent object (tower, skyscraper) or above a mountain top. High objects and orographic forms deform the electric field in the lower layer of the atmosphere. Above the prominent objects the strength of the electric field increases and it creates favourable conditions for the lightning path formation from the prominent top upwards and ionised channel development from below. The length of stages, the time interval between them and other characteristics in the development of this lightning are similar to those of cloud-ground lightning. In this case only the flash of the return current from the cloud base towards the peak near the ground is missing, but there is a series of consecutive strikes along the channel created by the initial lightning (Figure 9).

Figure 9. The channel of the initial lightning ground→cloud

Ball lightning

Ball lightning is created suddenly, lasts shortly and there are only several photos of it taken by accident. The first photograph was taken in the second half of the 20th century when the phenomenon occurred suddenly and the observer had a camera at hand (Figure 10). The ball lightning is described as a glowing one, with the radius of 10-20 centimetres, but there are recorded cases of radiuses of 1-2 metres. It is created after a thunder strike, it moves slowly, parallel to the ground or freely through the air. Occasionally it disappears silently, and sometimes it explodes in contact with a solid object (a wall or a tree).

It has been observed and described that ball lightning entered a house through an open window or a chimney, and then it either crumbled touching the wall or it curved and exited through the window. On one occasion a similar glowing ball, the size of an orange, was observed falling into a bowl with 5 litres of water and heating the water to the boiling point. Ball lightning is a rare phenomenon, when it occurs it is mainly in higher regions of the Alps. Still, there is no unique theory about the conditions in which ball lighting phenomenon appears, although according to the descriptions it occurs most frequently during thunderstorms.

Figure 10 Random footage of ball lightning taken in Maastricht, Holandija (By Joe Thomissen [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], from Wikimedia Commons)

New types of lightning

Three new types of lightning have been recently discovered. They are light phenomena occurring in the atmosphere above the tropospheric thundercloud cumulonimbus. The phenomena were captured during the night by ultra sensitive cameras and all of them may not occur simultaneously. The most striking are *blue jet, sprite and elve.*

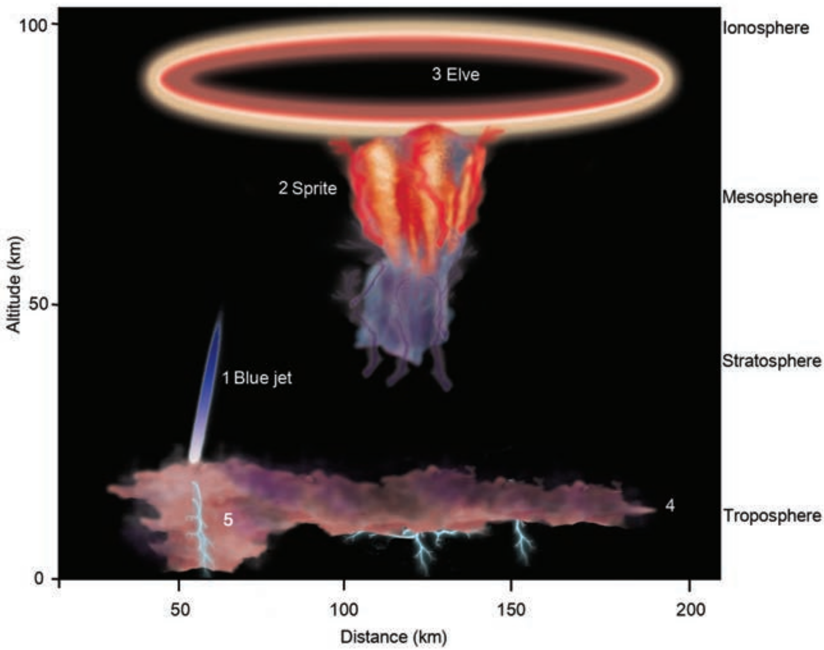

Figure 11. Light phenomena above a distinctive thundercloud distributed at various altitudes of the middle atmosphere

Numbers refer to the position of the light phenomena in the image:

(1) blue jet
(2) sprite
(3) elve
(4) thundercloud cumulonimbus
(5) cloud to ground lightning

Sprite lightning is formed at the attitude of about 70 km (mesosphere) as a light phenomenon of short duration which has the shape of fire flames directed downwards. This phenomenon may reach altitudes up to 90-100 km, i.e. to the ionosphere. It is a red light phenomenon from upper part of which the branches of flames descend downwards to lower layers of the atmosphere even to the altitudes of 25-30 km (stratosphere) and change their colour into a bluish tint. Sprites are usually triggered by very intensive electric discharges from a thundercloud towards the ground and they usually occur together. Distance measurements which revealed the occurrence of sprites in the atmosphere confirmed the descriptions of visual observations of the pilots from their cockpits which were not believed at first. Later on those descriptions (1970-1980) were collected and represented reliable information about the sprite phenomenon before instrumental monitoring was introduced. However, the visibility of sprites by the naked eye lasts for up to one tenth of a second, whereas the visibility of the phenomena is monitored by a sensitive night time camera up to one hundredth of a second. Sprites are usually joined with strong positive electric discharge between the cloud and the ground. In other words, a huge electrical spark appears above the thundercloud at altitude of about 70 km. The ionised channels of the spark are spreading like a bundle of threads to higher and lower layers. Sprites are not accompanied by thunder, but they may produce sound waves of low frequencies, about 1 Hz to which human ear is not sensitive.

Figure 12. Sprite formed between a thundercloud and a lower boundary of ionosphere (By Dramatic sky photography with a permission of Paul Smith)

Elve is formed as a red light phenomenon in the shape of a ring, a saucer or a doughnut at altitudes of 90-100 km. In its short duration interval it may spread to even several hundreds of kilometres (up to

400km) in radius. It was discovered in the early 1990s by the instruments from the Space Shuttle and by other remote instruments from the Earth's surface. Elves are products of an extremely strong electromagnetic impulse during a strong electric discharge in a thundercloud. Strong impulse advances towards higher altitudes and causes glittering of molecules in the surrounding atmosphere. The phenomenon lasts even shorter than the sprite, only several thousandths of a second at it is impossible to be seen by the naked eye.

YEAR

3

Teaching topic:

WAVE OPTICS

Teaching units:

1. Light spectrum
2. Light dispersion
3. Reflection, refraction and absorption of light
4. Light scattering

Atmosphere and atmospheric layers

The Earth's atmosphere is the layer of gases that surround the Earth due to the gravitational force of the Earth. The main role of the Earth's atmosphere is the protection of life on the Earth owing to the mechanism of absorption of ultraviolet part of electromagnetic spectrum of the Sun radiation.

The atmosphere is divided into layers according to different criteria out of which the most frequently used and well-known is the division according to atmospheric layers (Figure 1 and Figure 2) where the temperature depends on altitude (with regard to the surface of the Earth).

Troposphere: from the Earth's surface up to the altitude of 10km-15 km where the temperature decreases as the altitude increases

Stratosphere: from the altitude of 10km-15km up to the altitude of about 50km where the temperature increases with the altitude increase

Mesosphere: from the altitude of 50km up to the altitude of 80km where the temperature decreases as the altitude increases

Thermosphere: from the altitude of 80km up to the altitude of about 600km where the temperature increases with the altitude increase

Exosphere: above 800km of altitude where the atmosphere layer has low density

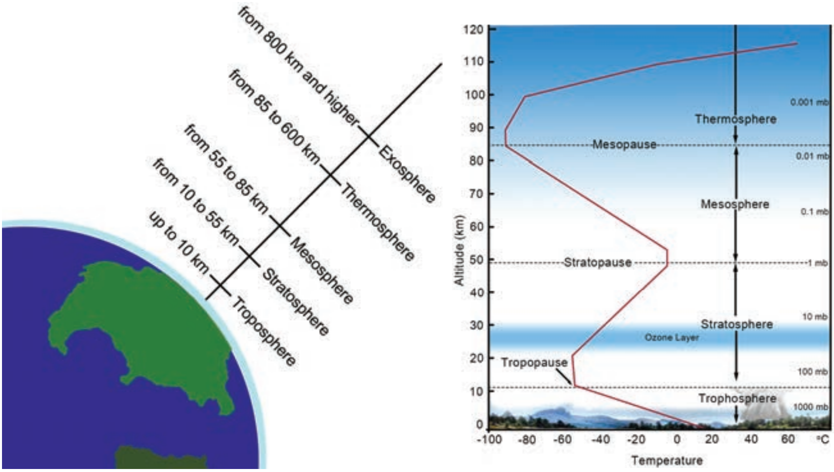

Figure 1 and Figure 2. Vertical structure of the atmosphere by layers - T=f(h)

Light spectrum

Light is the part of the electromagnetic spectrum of certain range of frequencies, i.e. wavelengths.

The basic feature of light is the frequency which is the same as the frequency of atoms which emit the light which is not changing. Wavelength is not the basic feature of light and it depends on the features of the medium through which light spreads. The medium through which the light spreads with higher speed is less optically dense medium and has lower index of refraction and vice versa. Wavelength of light is higher in a less optically dense medium and it is, naturally, the highest in vacuum.

Light as a part of the electromagnetic spectrum of radiation is divided into three parts:

- visible light
- infrared light
- ultraviolet light

Visible light is the part of the light spectrum which is visible to the human eye and has the range of wavelengths from 380nm to 760nm in vacuum. Wavelengths longer than 760nm belong to infrared (IR) and wavelengths shorter than 380nm to ultraviolet (UV) portion of the light spectrum.

The visible light spectrum is divided into characteristic areas each of them representing what is referred to in everyday speech as a colour, but it actually represents a certain range of wavelengths (in vacuum).

VIOLET	*(380–440) nm*
INDIGO	*(440–460) nm*
BLUE	*(460–510) nm*
GREEN	*(510–560) nm*
YELLOW	*(560–610) nm*
ORANGE	*(610–660) nm*
RED	*(660–760) nm*

As it can be seen from the illustration the longest wavelengths belong to the red part of the spectrum and the shortest wavelengths belong to the violet part within the visible light spectrum.

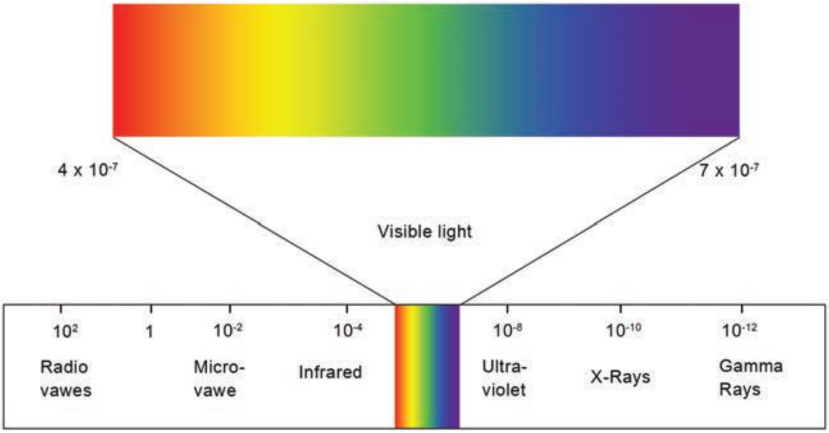

Figure 3. Light spectrum as a part of electromagnetic spectrum

When light passes through the Earth's atmosphere certain phenomena occur such as: light dispersion, light absorption and light scattering, Tyndall effect of light scattering, *Rayleigh scattering*, as well as absorption and emission spectra. Owing to these phenomena it is possible to explain the blue colour of the sky, red sky during the sunrise and the sunset, rainbow and other interesting effects. Therefore, these phenomena and effects will be explained in this part.

Light dispersion

Light wavelength depends on the characteristics of the medium it passes through. Such phenomenon is called dispersion and represents the dependency of the refractive index of the medium and light wavelength.

Roughly, the medium influences the light propagation due to interaction of the light and particles of the medium (atoms, molecules, etc.). Atoms and molecules of the medium through which the light passes consist of charged particles (protons and electrons). Those charged particles in atoms and molecules oscillate at their own frequency around their balanced equilibriums under the impact of quasi-elastic forces. The light has its own frequency (always the same), and the primary light wave causes forced oscillation of the medium particles. As a result, secondary waves appear around particles which are superposed with primary light waves and form the resulting wave. Amplitude and phase of the resulting wave differ from the previous and thus the light passes through the substantial medium at lower speed than through vacuum. If the forced oscillation of particles is stronger, the difference between the speed of light through vacuum and the speed of light through a substantial medium is higher.

Accordingly, the light of various wavelengths will pass through the same medium at different speeds and have different indexes of refraction. It is only in vacuum where the light of all frequencies passes at the same speed.

For example, refractive index of water for the red light (λ_c =670.8nm) is 1.33 and for the violet light (λ_{lj}=404.7nm) it is 1.34.

Dependency of the refractive index of wavelength is experimentally established and may be presented by the following formula:

$$\mathbf{n=a+b/\lambda^2}$$

where a and b are parameters (constants) for one type of substance.

If we graphically present the refraction index dependence of the circular frequency, we get a dispersion curve (Figure 4). It is observable that there are areas in which the refractive index increases with circular frequency increase (wavelength decreases) and those areas are called the areas of normal dispersion. However, there is also the area in which with the increase of circular frequency the refractive index decreases. It is the area of anomalous dispersion. This phenomenon is caused by a strong light absorption in cases when the light frequency is close to the frequencies of the atoms and molecules of the medium.

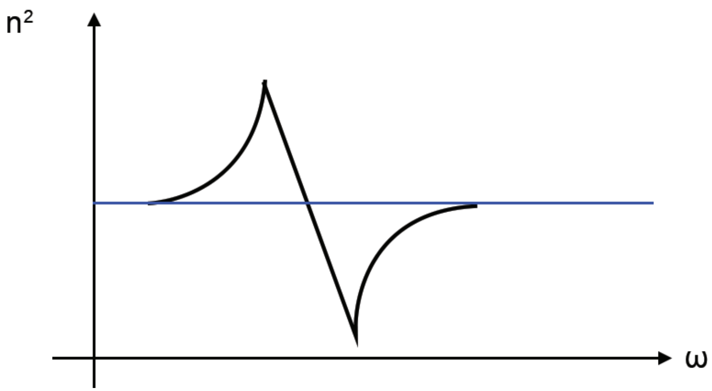

Figure 4. Circular frequency dependence of the refractive index square

Reflection, refraction and absorption of light

Three mechanisms take place when light passes through substance: reflection, refraction and absorption. Which mechanism is more dominant depends on different factors such as the substance composition, geometry, surface roughness.

Reflection of light occurs when the light encounters the boundary of two media, and it partially bounces off the boundary. The laws of reflection are:

1) the incident ray angle and the reflected ray angle are equal
2) incident rays, reflected rays and the normal to the boundary surface lie in the same plane

Diffuse reflection frequently occurs in the atmosphere as a consequence of the law of reflection from rough surfaces, when mutually parallel incident rays reflect at mutually different directions due to their different angles (Figure 5).

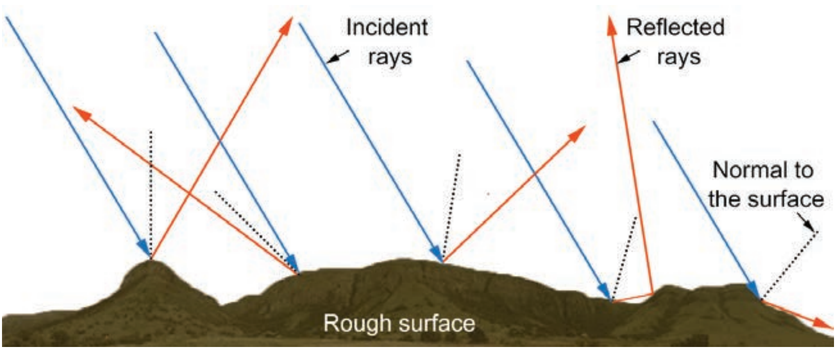

Figure 5. Diffuse reflection of light

Refraction of light represents the change of speed, wavelength and direction of the light passing from a medium with one reflective index into a medium with another reflective index (Figure 6).

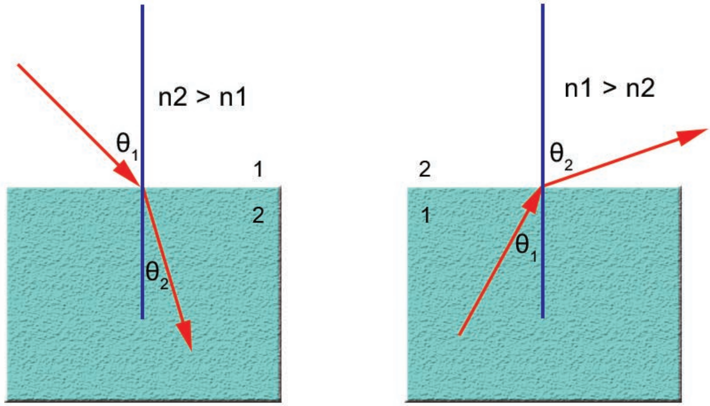

Figure 6 Law of refraction of light

Mathematical form of the law of refraction of light:

$$\sin\theta_1/\sin\theta_2 = c_1/c_2 = n_2/n_1$$

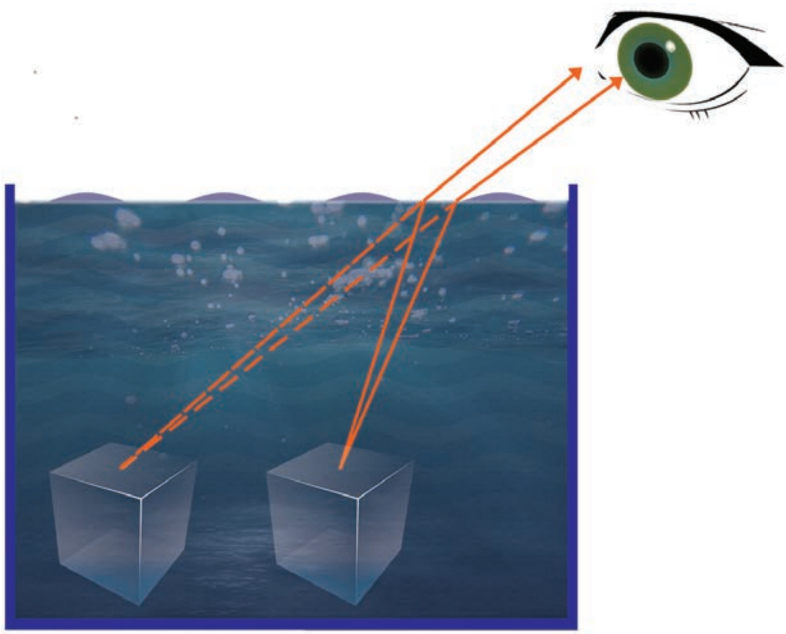

Figure 7. Apparent position of the objects in water as a result of refraction of light

There is a characteristic occurrence of *total reflection* when light rays do not pass into another medium, but completely reflect from the boundary surface. Total reflection is possible only at the boundary of more optically dense medium with less optically dense medium when an incident ray angle that is larger than the boundary angle for those two media (Figure 8).

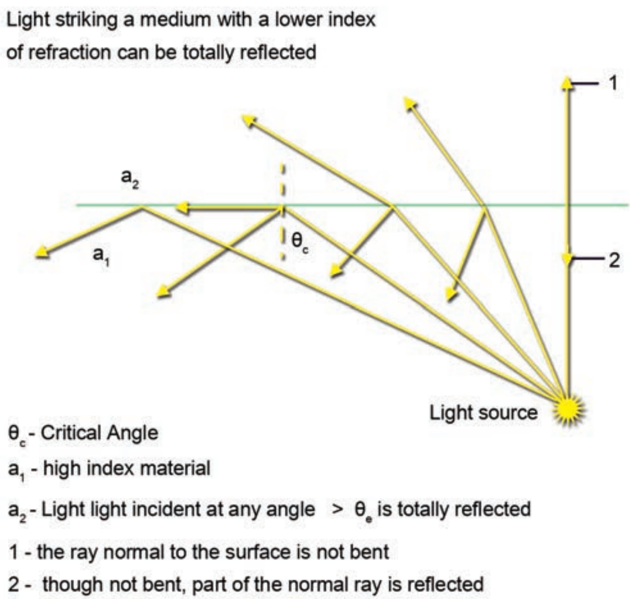

Figure 8. Total reflection and bordering angle of total reflection

Absorption is the occurrence of the decreasing intensity of light at passing through an optical medium. The light of different wavelengths is absorbed differently. According to the intensity of absorption, optical media are divided into transparent and opaque. The transparent medium is a weak absorber of all light wavelengths from the visible spectrum, whereas the opaque medium is characterised with strong absorption.

Division of optical media into transparent and opaque is provisional, since transparency, i.e. the level of absorption does not depend only on the substance type, but also on the thickness of the substance layer through which the light passes. For example, glass is classified into transparent media group, but it is also a strong absorber of ultraviolet and infrared part of the light spectrum. Moreover, water also belongs to transparent media group, but at greater depths in oceans there is only darkness.

Figure 9 illustrates the absorption of the Sun radiation dependent on wavelength and depth of water. It is obvious that the strongest absorption occurs with longer wavelengths (red) and the weakest absorption occurs with shorter wavelengths (violet). Similarly, it is obvious that the absorption is stronger at greater depths.

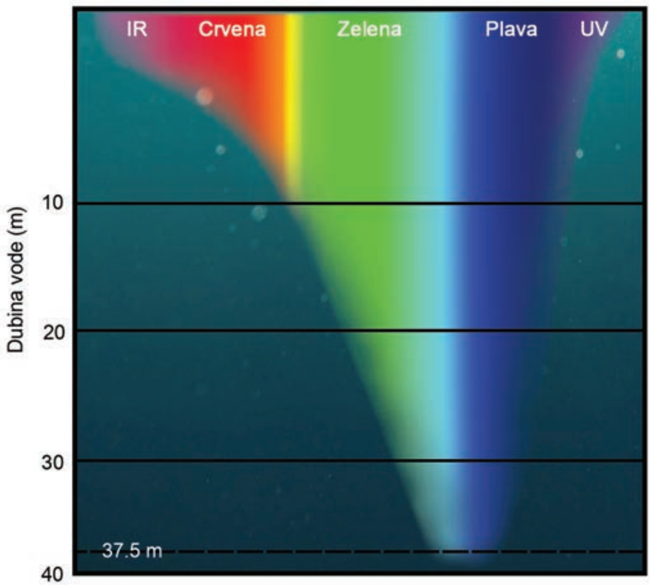

Figure 9. Water depth and light wavelength dependence of the Sun radiation absorption

Absorption phenomenon is explained by forced oscillations of electrons of the medium to which certain amount of energy of light is spent, transformed into another form and consequently the energy and intensity of the incident ray wavelength decrease. Thus, the consequence of the absorption is dispersion (especially anomalous dispersion) and weakening of the light intensity.

Intensity of light which propagates through optical medium decreases exponentially with the thickness of the layers through which the light passes, which is mathematically described by the law of absorption:

$$\mathbf{I=I_0\, e^{-\mu d}},$$

gde je

I_0 -intensity of the light when it enters the absorbent medium

I - intensity of the light when it exits the absorbent medium

d - thickness of the absorbent medium

μ - linear coefficient of absorption (attenuation) of the optical medium, i.e. absorbent medium

Linear coefficient of absorption depends on the type of medium and light frequency. The law on absorption is valid for all types of waves, not only for light waves.

Colour of the object depends on the nature of the object and the light that falls on the object. The objects may be observed in reflected and transmitted lights, i.e. the colour of the objects is defined by the wavelengths that are reflected, i.e. those wavelengths that are transmitted, depending on the more dominant effect. For example, if the object absorbs all wavelengths except blue light, the object will have either a certain shade of blue or a set of blue shades in transmitted light. The objects that selectively transmit light of certain frequencies are called *optical filters*.

If an object is non-transparent it will be visible in reflected light, i.e. it will have the colour of the reflected wavelength. Most of the substances do not reflect and transmit light waves of only one colour, but of more colours and their colour is the combination of several basic colours.

When an object reflects all light wavelengths, it has *white colour*, but when it absorbs all wavelengths, it has *black colour*.

Absorption of light occurs in the Earth's atmosphere due to the interaction between light waves and particles in the atmosphere (molecules of dry air, water vapour, dirt in the air). The ozone layer highly absorbs ultraviolet radiation and lower layers of the atmosphere absorb infrared radiation. Moreover, gases in the atmosphere absorb certain light wavelengths (each gas has a different spectrum of absorption).

There is greater absorption of light in the Earth's atmosphere at higher latitudes since the path the light travels is longer. This may be helpful in explaining certain light effects that will be described later on.

Light scattering

The propagation of light rays through homogenous optical media (density is the same in every part of the medium, i.e. refractive index) is linear. If the medium is inhomogeneous then the light beam bends away from normal, i.e. *light scattering* occurs.

Optically inhomogeneous media are the media in which the refractive index is not the same in every part of the medium and parts of the wave front propagate through it at different speed. For instance, the medium is inhomogeneous if there are random fluctuations of density within the medium or if there are particles that according to their composition do not belong to that medium.

Light scattering may be observed as diffraction at such inhomogeneities, which due to chaotic (thermal) movement constantly change their position in time, i.e. their distribution is always changing.

There are various types of light scattering due to the abovementioned causes of light scattering.

The Tyndall effect is the type of light scattering which occurs in a medium with inhomogenities of different refractive indices which are smaller with reference to the light wavelength. The examples of such media, which are also called *opaque media,* are: fog, colloides, suspensions, smoke, dusty air, and liquids with micro particles. It may be assumed that at such homogeneities there is no diffraction of light. The intensity of scattered light is not the same in all directions, but it is symmetrically distributed regarding the direction of the incident ray of light.

In media with little opacity there is so called *opalescence.*

Figure 10. Opalescence in a crystal (https://www.flickr.com/photos/optick/112909824/) [CC BY-SA 2.0 (https://creativecommons.org/licenses/by-sa/2.0)], via Wikimedia Commons)

Figure 11. Light scattering in the atmosphere in the woods

The most frequent form of light scattering is *Rayleigh scattering*. It is elastic scattering of light off the particles with dimesions less than one tenth of a wavelength, i.e. off the atoms and molecules. This type of scattering is a prominent feature of gases, but it is possible in other media as well.

The intensity of scattered light is proportional to the fourth power of frequency and inversely proportional to the fourth power of light wavelength.

$$\mathbf{I \approx \nu^4 \,;\, I \approx 1/\lambda^4}$$

This equation is called *Rayleigh's law.* When polychromatic light scatters within the opaque medium, the scattered light is blue because according to *Rayleigh*'s law blue colour (smaller wavelength) disperses stronger than red and yellow (higher wavelength), and as the consequence white light that passes through the opaque medium becomes reddish.

Mie scattering is a phenomenon not strongly wavelength dependent but responsible for light scattering on particles (inhomogenities) sizes of which are about the size of wavelength or larger. This type of light scattering causes white glare around the Sun when a lot of particulate material is present in the air and it is also responsible for whitish forms, fog and mist in the air (Figure 12)

Figure 12. Whitish clouds

Molecular scattering occurs if the medium is chemically homogenous (clear liquids and gases) but there are fluctuations in density that represent inhomogenities.

Optical effects in the atmosphere

As a result of optical phenomena in the atmosphere described in previous chapters, there are various optical effects which may be explained by means of those phenomena. The most famous optical effects are:

- decomposition of light
- rainbow
- fata morgana

– polar light
– blue skies
– red sunset and sunrise
– halo

Decomposition of light

When polychromatic light falls onto a glass prism, the light will be separated into its component colours and the range of visible colours produced after refracting through the prism is the colour spectrum. This phenomenon was first experimentally explained by Newton (Figure 13) when he positioned the prism under the beam of the Sun rays that were passing through a circular hole on a window glass. Behind the prism there was not the circle but the ribbon with colours between which there were gradual transitions and the order of colours remained the same in all the experiments.

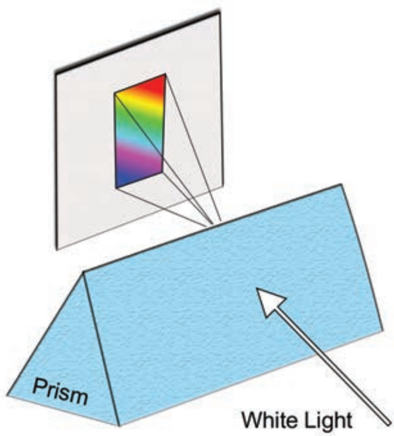

Figure 13. Schemata of Newton's experiment in which dispersive spectrum was created

This phenomenon of decomposition of polychromatic light into its components is the consequence of dispersion of light, i.e. the fact that the light of various wavelengths propagates at different speeds through certain optical medium, with different refractive indices for different wavelengths.

The spectrum obtained by decomposition of white (polychromatic) light on its frequencies or wavelengths is called *dispersive spectrum* (Figure 14)

Light with different wavelengths (different colours) refracts under different angles according to the law of refraction. The light with the highest wavelength and the smallest frequency (red) refracts under the smallest angle of refraction. The light with the smallest wavelength and the highest frequency (violet) refracts under the biggest angle of refraction.

For example, when light rays pass from air into water under the incident angle of 45^0, violet colour (λ_{lj}=404.7nm; n_{lj}=1.34) refracts at an angle of 31.85^0 and red colour (λ_c=670.8nm; n_c=1.33) at an angle of 32.12^0.

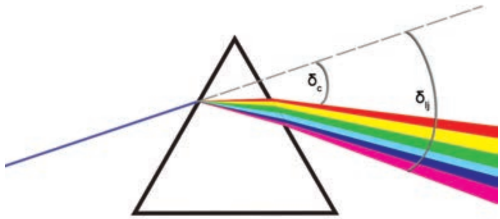

Figure 14. Dispersive spectrum and width of dispersive beam

When colour spectrum is obtained after decomposition of polychromatic light through a prism, then another prism is put in the reversed position with regard to the first one, the decomposed light is recombined and becomes polychromatic exiting the second prism (Figure 15).

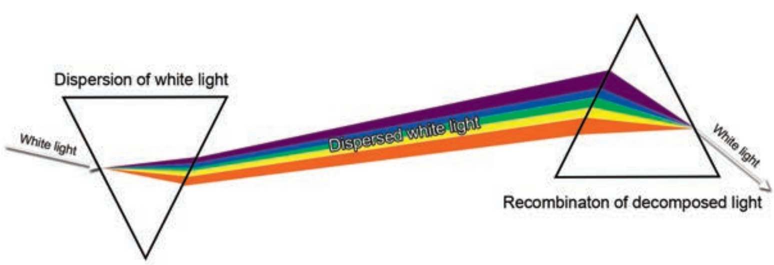

Figure 15. Dispersion of white light and recombination of dispersed light by means of two prisms second of which is in inverted position

Rainbow

Rainbow is one of the most famous optical effects in the atmosphere. The observer may see a rainbow if the Sun is behind his back and drops of water in front of him (rain drops, fountain, waterfall, etc.). The Sun needs to occupy a certain position. Rainbow is not an immovable object in the sky, it actually moves. Every observer can see "his own" rainbow, perceived from his specific position.

Rainbow phenomenon is explained on the basis of the total reflection and dispersion of light in drops of water.

Rainbow phenomenon can be explained and illustrated in the following ways (Figure 16 and Figure 17).

A light ray refracts when entering a drop of water and decomposes since there is different refractive index of water for different wavelengths. Violet colour bends the most and red colour the least. On the other end of the drop the total reflection occurs, light rays are refracted again and when exiting the drop there is additional broadening of the light spectrum. The described phenomenon occurs in immense number of drops and it is observed as the rainbow which is visible at certain direction depending on the Sun's position.

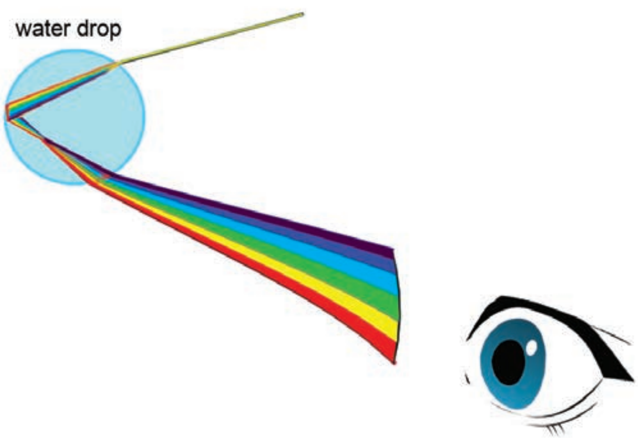

Figure 16. Refraction and total reflection in water drops at rainbow formation

Figure 17. Rainbow

The main rainbow is observed at an angle of 42^0 with reference to the horizon. Sometimes, above the main rainbow there is a secondary rainbow whose colours have a reverse order with regard to the main rainbow. The secondary rainbow is observed at the angle of 51^0 (Figure 18).

Figure 18. Main and secondary rainbow

Fata morgana

Fata morgana is an optical effect in the atmosphere where objects are seen in the distance shifted to an incorrect position, but actually positioned at another place out of the sight of the observer.

Fata morgana belongs to the group of phenomena called mirage. There are inferior and superior mirages with regard to the position of the optical effect compared to the position of the real object. Fata morgana is a superior mirage. It is formed above a cold surface at inverse temperature distribution, i.e. in the layers of the atmosphere where the temperature increases with altitude increase. At bordering surfaces between those layers there is the refraction of light rays arriving from distant objects out of sight and there is the total refraction of light rays entering the layer at small angles. That causes that the image of the object is formed at the intersection of rays that have been totally reflected. The observer, in fact, does not see directly the object itself, but its imaginary form.

Fata morgana occurs most frequently in deserts (Figure 19), but it may also occur at sea (Figure 20).

Figure 19. Fata morgana at sea

Figure 20. Fata morgana in the desert

Inferior mirages occur above overheated surfaces when there is great temperature decrease with altitude increase (high vertical temperature gradient). For example, above the desert sand or hot asphalt (Figure 20, Figure 21).

Figure 21. Inferior mirage on hot asphalt (By Yuri Khristich [CC0], from Wikimedia Commons)

Halo

Halo is a general term for a group of optical phenomena that are formed by refraction and reflection of light on icy crystals in clouds. It may be observed when cirrostratus clouds are in the background (fluffy layered clouds). Halos usually form when calm weather and clear skies replace windy weather, atmospheric pressure decreases and the sky is whitish. The Sun and the Moon appear to glow through milk glass (Figure 22)

Figure 22. Halo effect around the Sun

The 22° halo is a ring of rainbow colours around the Moon. It was named after its inner angular diameter. The light that arrives from the Moon hits the clouds with ice crystals where it refracts at different angles, but the most intensive is the light which bands the least from its direction, i.e. the one which refracts at the smallest angle. The angle is approximately 22°. These light rays form the inner circle of the ring and the ring is 22° distant from the Moon. Since there are no light rays that refract at a smaller angle, the area between the Moon and the halo is dark.

The inner part of a halo is the brightest. The halo becomes reddish in that part since red light rays refract less than the rays with smaller wavelengths. Then follow yellow, green and blue colours of the ring.

Sometimes the *46° halo* is formed, but it is rarely seen as the complete ring. Usually only some parts of a halo are visible. This halo has the same colour scheme as the 22° halo, but it is less bright.

Both halos may appear around the Sun as well, but they cannot be seen as clearly as around the Moon, since the Sun's light disables clear visibility.

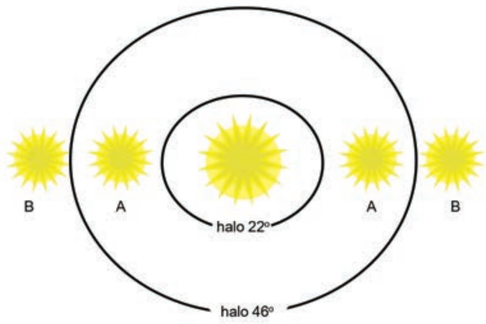

Figure 23. The 22° Halo and the 46° Halo and the parhelic circles 22°(A) and 46° (B).

They do not appear together.

When the refracting rims of ice crystals are normal to the horizon then we may observe sharply defined bright spot in the sky which seems as the Sun – the effect known as *the fake Sun* (Figure 24)

Figure 24. Fake image of the Sun above the Stonehenge (By Timdaw [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons)

The most frequent are two fake suns. These two fake suns the 22° halos are red towards the Sun and change colour on the opposite side the same as halos. The higher the Sun is over the horizon, the fake suns are at larger distance, and when the Sun reaches the height of 60° 45' the fake suns disappear.

Blue skies and red sunset and sunrise

Blue skies and red sunset and sunrise have the same origin. They are the phenomena of light scattering in the Earth atmosphere where the light is scattered by molecules and atoms. According to Rayleigh's law, the intensity of scattered light is inversely proportional to the fourth power of the wavelength. The consequence of this law is that small wavelengths are scattered the most, in this case blue light. Thus, the spectrum of scattered light shifts towards the blue part of the spectrum. The observer observes the sky where the blue light is scattered the most, therefore the sky has the blue colour (Figure 25).

The Earth's atmosphere consists of oxygen, nitrogen, argon, water vapour, ice crystals and dust too. The ozone layer is also the part of the atmosphere. At first, it was thought that the sky is blue because ozone and water absorb red part of the spectrum and transmit the blue part of the spectrum. However, water and ozone are not present in such quantities to absorb that large quantity of the red light. Tyndall assumed that the blue light scattering occurs at dust particles and other pollutants and that the light would pass without scattering through the unpolluted air. Later on, his assumption was proved wrong.

Figure 25. Blue skies

British scientist Rayleigh explained that the air is the main cause of the blue colour of the sky, i.e. molecular scattering. When the sunlight travels through the atmosphere one portion of it passes through molecules of gas in the atmosphere and reaches the ground preserving its white colour completely. However, the other portion of the sunlight collides with the molecules of gas (e.g. nitrogen or oxygen), which absorb it and then it is scattered to all sides. The atoms in the molecules of gas are excited under the influence of the absorbed light and reemit light photons of all wavelengths, from red to violet, into all directions around molecules. Thus, one portion of the sunlight continues to travel towards the ground, another portion is sent into the sky and the remaining portion returns towards the Sun. Wavelengths of light emitted by molecules depend on the energy: on one photon of red light there are eight photons of blue light. Therefore, blue light emitted by molecules is eight times stronger than the red light and thus the sky appears blue. However, the sky is not completely blue, because other colours also travel to our eyes, but they appear very pale because they are dazzled by the extremely bright blue.

The consequence of the intensive light scattering of the blue spectrum is the red sky at sunset and sunrise. The observer looking towards the Sun observes the light that has passed through the atmosphere without scattering. In both cases the Sun is very close to the horizon, i.e. the light travels the longer path to the observer. On that longer path blue light is even more scattered and the spectrum of transmitted light shifts towards higher wavelengths, i.e. the red part of the spectrum; and the observer sees the red colour around the Sun, with the lower part of the Sun disc being more red than the upper (Figure 26).

Figure 26. Redness of the Sun at sunrise and sunset (upper and lower discs)

Polar lights

A polar light is the phenomenon which occurs near magnetic poles of the Earth and manifests in the form of foggy or misty patches of light in various colours. If it is at the North Pole, it is called *aurora borealis*, and at the South Pole it is called *aurora australis.*

When the Sun's activity is intensive there are eruptions of solar flares that produce charged elementary particles which form the solar wind. The particles from the solar wind travel to the Earth and are captured by the Earth's magnetic field. Since the charged moving particles are acted upon by the Lorentz force in the magnetic field, with the force's direction normal on the direction of particles velocity, the force changes the direction of movement of the particles and forces them to move on curved paths, i.e. the particles bend towards the poles.

The particles move at high velocities and emit electromagnetic radiation. In the upper layers of the atmosphere, usually at altitudes 80-150km in the Earth atmosphere, the particles interact with neutral molecules and atoms of gas which become excited and emit light while returning to lower energetic levels. The light is the product of recombination of electrons and ions. The emission of atomic oxygen prevails in the light – red line at 557.7 nm (Figure 27) and (with electrons of lower energy and at higher altitudes) - dark red line at 630.0 nm (Figure 27). Both lines originate from forbidden transfers of atomic oxygen from energy levels that are (in the absence of collision) stable which explains slow brightening and fading (0.5 - 1 s) of aurora's flames. Many other spectral lines are also present, especially the ones of molecular nitrogen.

Aurora occurs either as "diffuse light" or as a "curtain aurora" spreading in the east-west direction. Sometimes there are "calm arches" and sometimes the light constantly changes in the sky ("active aurora"). Each curtain aurora consists of numerous parallel signs directed towards local magnetic field which leads us to a conclusion that aurora is caused by the Earth's magnetic field.

The occurrence of polar light is related to *magnetic storms* which are interrelated with eleven year cycle of the Sun's freckle activities. Moreover, it has been noticed that geomagnetic storms mostly occur during the equinox, in early spring or autumn what is a bit mysterious since the activities at poles are not related with seasons.

Figure 27. Reddish polar light (λ= 630.0 nm)

Figure 28. Green polar light (λ=557.7 nm)

Teaching topic:

ELECTROMAGNETIC WAVES

Teaching units:

1. Ultraviolet and infrared radiation
2. Absorption spectra
3. Diffuse reflection
4. Absorption of radiation

Spectrum of electromagnetic waves. Types of spectra

Spectrum of electromagnetic waves consists of different wavelength radiation, i.e. frequencies. The range of wavelengths (frequencies) is wide, from about 10^8 m to 10^{-17} m (from 1Hz to 10^{25} Hz)

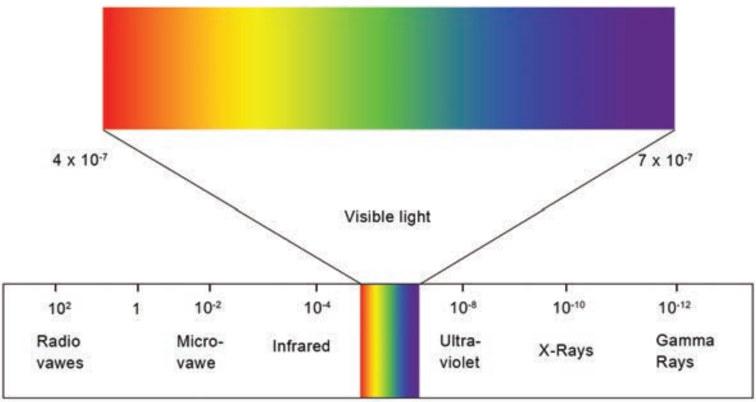

Figure 1. Electromagnetic radiation spectrum (continuous spectrum)

The part of the electromagnetic waves spectrum which ranges between 760nm and 1cm is called infrared and the part of the electromagnetic waves spectrum ranging between 10nm and 380nm is called *ultraviolet*. Infrared radiation passes through the clouds and fog, whereas ultraviolet is mainly absorbed in the atmosphere.

There are different spectra of light radiation which originate from the objects in different states of matter and at high temperatures.

Hot solids and liquids emit *continuous spectra.*

Hot gases with multi-atomic molecules emit *ribbon spectra.*

Hot mono-atomic gases emit *line spectra*. In such spectra there are only particular wavelengths (lines).

All these spectra are the consequence of light radiation emission and they are called *emissive spectra*.

If white light passes through mono-atomic gas, the gas will absorb certain components of continuous spectra and a dark line will appear in that place. Such spectra are called *absorption spectra*. The position of the dark lines in the absorption spectrum of one element corresponds to the position of the lines in its emissive spectrum. It is defined by *Kirchhoff's law of absorption*:

Atoms of a certain element absorb the light that they emit under the same circumstances.

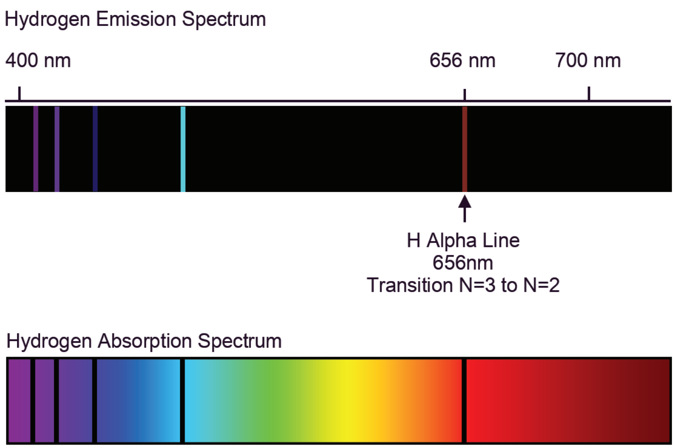

Figure 2. Absorption and emission line spectrum of hydrogen

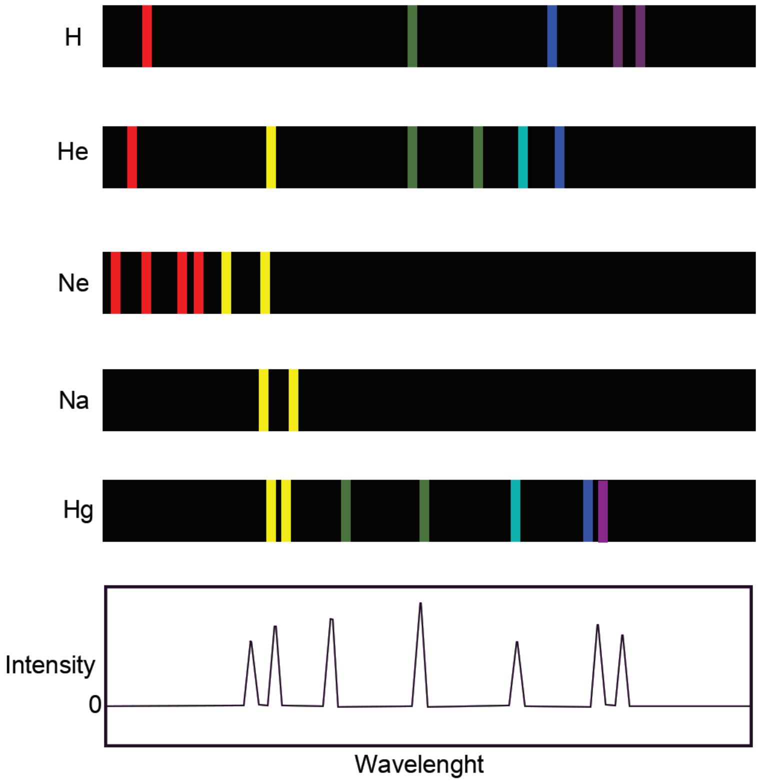

Figure 3. Emissive line spectra of various substances

Absorption of ultraviolet radiation as a factor in the origin of life on the Earth

Ultraviolet radiation (hereinafter: UV radiation) belongs to the category of shortwave radiation, small wavelengths, i.e. high energy. Owing to its high energy, interaction of UV radiation with living organisms is very dangerous and destructive. Therefore the absorption of UV radiation is of high importance. Among other things, numerous theories on the origin of life on the Earth are based on the mechanisms of absorption of UV radiation by water and ozone in the atmosphere.

The Earth was formed approximately 4.5 billion years ago. Packed with volcanoes and hot springs, the Earth was bombed by meteors and comets; it was rotating and cooling down. Volcanic eruptions emitted gases: carbon-dioxide, carbon-monoxide, nitrogen-oxides, and water vapour. Liquid water was the initial precondition for the first forms of life (cyanobacteria) that could carry out photosynthesis. After a long process of cooling down, when the temperature dropped to below 100^0C, water remained on the Earth surface initiating the formation of the oceans. It was only in the ocean (water is almost ideal absorber of UV radiation) where cyanobacteria could be formed and oxygen released in the photosynthesis process. Oxygen was emitted in the first atmosphere and additionally lowered the intensity of UV radiation that was arriving from the Sun into the ocean. It also helped the survival of the first forms of life by the thinning of the water layer and thus enabling the life forms to move towards the water surface. The first land plants appeared after about 2 billion years. The present atmosphere consists mainly of the same gases as the first atmosphere in its early stage but in a completely different proportion.

Absorption spectrum of the atmosphere. Importance of the ozone layer

Besides water, one of the most powerful absorbents in higher layers of the atmosphere is ozone. Most of the gases in the atmosphere absorb electromagnetic radiation of different wavelengths within a particular range of wavelengths. Ozone almost totally absorbs UV radiation (under 0.3 μm) practically preserving life on the Earth. Nitrogen and oxygen absorb even shorter waves in the atmosphere, under 0.1 μm and 0.245 μm, respectively. However, within the range of visible light, from 0.3 μm to 0.8 μm, atmospheric absorptivity is zero, i.e. absorption spectrum has a spectral hole. It enables the Sun radiation to reach the Earth's surface without the harmful UV part of the spectrum.

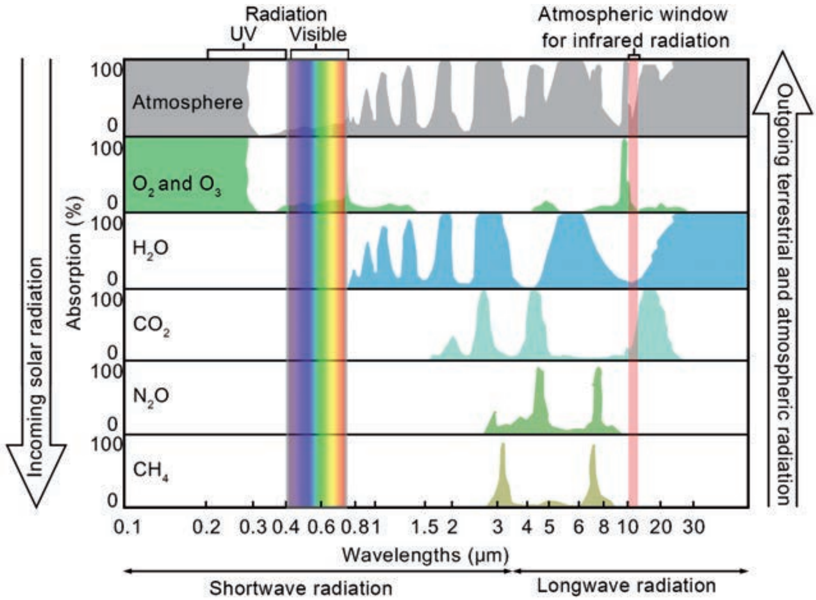

Figure 4. Absorption spectra of atmospheric gases

The Greenhouse Effect

Along with shortwave solar radiation, longwave or infrared radiation which is emitted by water vapour, clouds and particles in the atmosphere as their thermal radiation also reaches the Earth. This radiation has wavelengths above 2 μm. However, the most significant source of longwave radiation in the atmosphere is the Earth itself. The greenhouse effect occurs owing to that radiation and the absorption spectra of gases in the atmosphere.

The name of this effect is kept for historical reasons, although the effect is a completely different physical process from the one occurring in greenhouses to which the name referred to at first. In those two physical processes, classical greenhouse and greenhouse effect, there is only one similar consequence - the air temperature increase. However, the causes and mechanisms of air temperature increase in both processes are completely different.

In greenhouses the air temperature increase is achieved by means of glass walls and a ceiling that prevent heat conduction, i.e. heat removal from the inside into the surroundings. The heat energy that is captured inside causes the temperature increase which is necessary for the purposes that need to be achieved by a greenhouse. With the greenhouse effect the gases in the atmosphere absorb longwave radiation in so called infrared window, i.e. the range of wavelengths from 2 μm to 10 μm. Owing to this, the atmosphere heats and then emits radiation towards the surface of the Earth (radiation reemission). The Earth partially absorbs the radiation and partially reflects it then the Earth reemits a portion of the absorbed radiation into the atmosphere. All those mechanisms have their final result in the temperature increase in the atmosphere.

Hence, two completely different processes are discussed here. The first one is the isolation and prevention of conducting radiation and the second one is absorption of longwave radiation and its reemission towards the Earth's surface.

Shortwave and longwave radiation in the atmosphere

Electromagnetic radiation arriving to the Earth from the Sun has the role of the most significant initiator of all processes in the atmosphere. Gases in the atmosphere do not absorb solar radiation in visible part of the spectrum (380 nm - 760 nm) thus high energy (shortwave) radiation reaches the Earth's surface.

The radiation that reaches the Earth's surface is the result of several mechanisms of the solar radiation attenuation. Those mechanisms are: radiation absorption, diffuse reflection and selective radiation absorption. The mechanisms significantly impact the quality and quantity of the solar radiation which reaches the Earth's surface.

Diffuse reflection occurs when electromagnetic radiation hits rough surface. The incidence rays are parallel, but the reflected rays are not parallel. It does not signify that the law of reflection is not valid, but the other way round. The rough surface behaves as a range of connected tiny flat surfaces so that the angles of parallel incident rays are not equal.

This is also valid for the angles of reflected rays. In the Earth's atmosphere there are particles, drops, parts of clouds which altogether play the role of rough surface and cause diffuse reflection it the atmosphere itself.

Selective absorption is the phenomenon of absorbing radiation of different wavelengths by a molecule at various intensities. This is the consequence of the fact that each gas has its own absorption spectrum which is its ”finger print”. Each gas at certain wavelengths has larger or smaller absorption capacity, i.e. selective absorption of radiation. The consequence is that dominant gases in the atmosphere will enable higher radiation absorption of wavelengths specific for their absorption spectrum, i.e. the intensity of solar radiation of those wavelengths will be decreased after propagation through the atmosphere.

Longwave radiation on the Earth. Higher or lower concentration of gases in particular parts of the atmosphere impacts the formation of the solar radiation spectrum which arrives to the Earth surface. Electromagnetic radiation that travels from the Sun passes through the Earth's atmosphere and reaches the Earth's surface has short wavelengths (high energy). The Earth's surface registers that radiation spectrum and then reemits the portion of the received radiation into the atmosphere. Reemitted radiation has lower energy and long wavelengths. The Earth's surface does not act in concordance with Stefan-*Boltzmann* Law of radiation. According to this law, the total emissive power of an object is proportional to the product of emission area and the fourth power of absolute object temperature. All parts of the Earth's surface neither have the same temperature nor the same emissive power, thus this law is applied for each part of the surface separately, e.g. emissive power of water surface is 0.96, forest 0.98, etc.

Longwave radiation in the atmosphere. Longwave radiation of the Earth is reemitted into the atmosphere, where certain processed of absorption and scattering occur and part of the radiation returns to the Earth's surface. That radiation is also longwave radiation but more complex than the outgoing terrestrial radiation. Every particle in the atmosphere, part of a cloud and gas component act as sources of thermal radiation in concordance with Stefan-*Boltzmann* Law. The surrounding air for all these particles is an infinite heat reservoir and it could be considered that the temperature of each particle is equal to the temperature of the surrounding air. The exact relation for calculating atmospheric radiation is impossible to formulate, although there are many empirical relations. Each of them is formulated according to the dominant atmosphere content. Reemitted radiation of the atmosphere belongs to the infrared part of the spectrum (4μm-10μm) with maximum radiation 10μm. It is longwave radiation. Common term in scientific literature for the radiation emitted by the Earth is the Earth's outgoing terrestrial radiation, and longwave radiation reaching the Earth from the atmosphere is called atmospheric radiation or atmospheric counter radiation. Frequently used mutual term is terrestrial radiation. The difference between the two radiation types is effective outgoing terrestrial radiation. This radiation is responsible for cooling and heating of the Earth's surface and the atmosphere during the night. The ground is heated during the night if the balance is positive, i.e. if the counter radiation is more intensive and vice versa. Presence of the clouds increases the balance of longwave radiation since terrestrial radiation and a part of the atmospheric counter radiation which is directed upwards hit the clouds and return to the Earth and cause slowing down of the cooling process during the night.

Energetic balance. Radiation impact on vegetation and vegetation impact on radiation

Solar radiation reaches the Earth's surface in two forms: direct and diffuse. Direct radiation arrives in the form of a radiation beam within a small spatial angle (up to 5^0), whereas diffuse radiation arrives after diffuse reflection and scattering in the atmosphere. The sum of the intensities of these two types of radiation is defined as *global radiation.* If the sky is clear, both types of radiation are present. In case of thicker layer of clouds only diffuse radiation reaches the Earth's surface. Throughout the year distribution of the solar radiation that reaches the Earth's surface changes significantly with latitude.

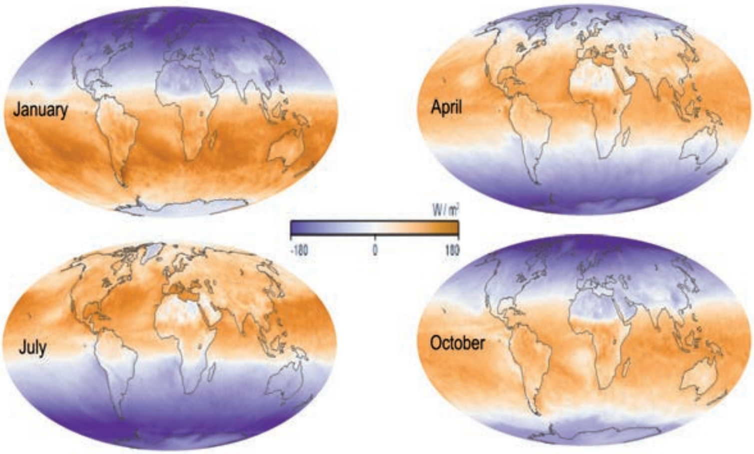

Figure 5. Distribution of global radiation (W/m²) on the surface of the Earth during a year

Global radiation may be absorbed on the surface or reflected back to the atmosphere. The relation between reflected and global radiation is defined as the surface *albedo*. The surface albedo depends on the structure, colour, moisture and characteristics of the surface layer. Moisture decreases albedo, because water that replaces air in the ground has higher specific heat capacity than air. Therefore, there is a larger portion of absorbed part of global radiation, i.e. it reflects less and thus the albedo decreases. Darker areas also decrease albedo because they absorb radiation better, while deep furrows increase the number of areas with different angles which further leads to multi-reflection radiation and more energy is kept in the ground. Thus, albedo as a very significant characteristic of the Earth's surface may be changed by altering the features of the surface. It may be concluded that similarly to the radiation affecting vegetation, there is also vegetation affecting radiation process. Radiation impacts plants by means of its energy (which depends only on frequency, i.e. radiation wavelength). From the point of view of plant physiology, light radiation is responsible for photosynthesis, chlorophyll formation, growth, shape and quality of plants.

Visible part of the solar radiation spectrum is useful, but the UV-B part (280nm-315nm) affects the photosynthesis negatively, i.e. the size and quality of the plant. Moreover, it decreases plant disease resistance.

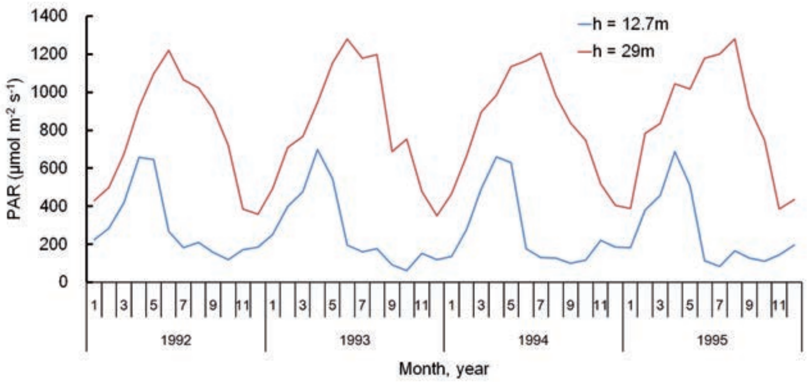

Figure 6. Intensity of photosynthesis active radiation above (red) and inside (blue) the forest

Vegetation impacts radiation by influencing the energetic balance of the surface. Different types of vegetation on the surface of the Earth have different absorption, reflection and transmission spectra due to their different morphological and physiological characteristics. All these issues impact global warming and the balance of energy in the end.

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- from the book "Agricultural Meteorology and Climatology" B. Lalić, J. Eitzinger, A. Dalla Marta, A. Firanj Sremac, S. Orlandini, and B. Pacher, Florense University Press: FORCE. BASIC PRINCIPLES OF ROTATION DYNAMICS (slike 2, 6), TERMODINAMIKA (1, 2, 3, 4, 5), MOLECULAR THEORY OF SOLIDS AND LIQUIDS AND PHASE TRANSITIONS (2, 3), THERMODYNAMICS (1, 2, 3), WAVE OPTICS (2, 3, 6), ELECTROMAGNETIC WAVES (1, 4, 5, 6)

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