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ENVIRONMENTAL BIOPHYSICS

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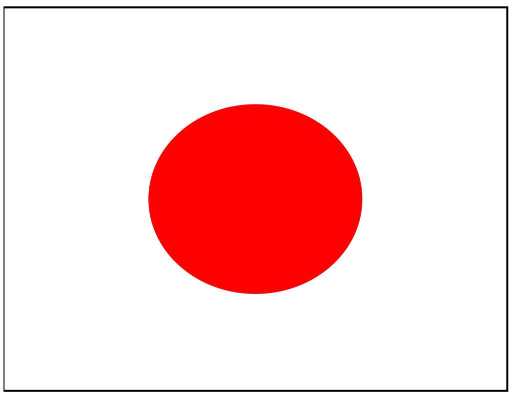

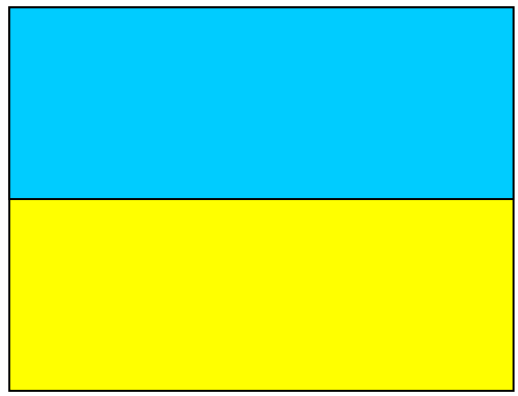

JSPS特別セミナー

CONTENTS

*"Biophysics includes everything
that is interesting
and excludes everything that is not"*
(K.S. Cole)

INTRODUCTION

Principal Terms

Biophysics, discipline that studies physical mechanisms and processes which are the basis of vital activity of biological objects; it is associated with the application of the physical principles, methods and instrumentation to living organisms or systems.

Environment (from French *environ* – "near", "around", "round about"; *environs* – "surroundings"; *environner* – "to surround"), the complex of the circumstances, objects, or conditions surrounding a living organism or an ecological community; it includes the combination of abiotic and biotic factors that affect the vital activity, form of existence, growth, development, and survival of living organisms (people, plants, animals, microorganisms).

Factor is cause or driving force that acts upon some process which takes place in the environment.

Parameter is a quantity that defines certain property of process or phenomenon that occurs in the environment.

Abiotic Factors are the components and phenomena of non-living nature which affect the ability of living organisms to survive in an environment.

F.e.: physical (pressure, wind, humidity, temperature, solar radiation, ionizing radiation); atmospheric, hydrographic, edaphic factors.

Biotic Factors are the sum total of factors produced by living organisms that affect the ability of other living organisms to survive in an environment.

F.e.: co-operation, competition, parasitism.

The *biosphere* is the region of the active life that includes lower part of atmosphere, hydrosphere and upper part of lithosphere. The biosphere's doctrine was developed by Vladimir Vernadsky in 1926.

An *ecosystem* is united natural complex which is formed by of all plants, animals and microorganisms and by their surroundings. The term ecosystem was introduced at first in 1930 by Roy Clapham, to denote the physical and biological components of an environment considered in relation to each other as a unit. British ecologist Arthur Tansley later refined the term, describing it as the interactive system established between *biocenosis* (a group of living organisms) and their *biotope* (the environment in which they live).

The *Earth's Atmosphere* is a gas layer surrounding the planet Earth; it consists of 78.1% of nitrogen, 21% of oxygen, 0.9% of argon, and trace amounts of other gases and water vapour. The Earth's atmosphere consists of the Troposphere, Stratosphere, Mesosphere, Ionosphere (or Thermosphere), Exosphere and the Magnetosphere.

The *lithosphere* is the solid outermost shell of a rocky planet that includes earth-crust and the upper part of mantle.

The *hydrosphere* describes the sum total of water objects of the Earth found on, under, and over the planet's surface. It includes the oceans, seas, lakes, rivers, underground waters, artificial watersheds, glaciers, cover of snow.

Objectives of the Text-Book

This text-book:

1) provides a description of physical surrounding of living organisms;
2) elucidates the ability of living organisms to respond to the change of external factors due to receptor systems and to choose optimal conditions of survival;
3) gives information on the principles of operation of modern instrumentation for measurement of the environmental parameters with special emphasis on automated system and remote sensing of environmental components;
4) reviews transfer phenomena and processes which characterise the interaction of living organisms with the environment;
5) considers the main principles of the solar radiation budget and the energy balance of physical and biological systems with the environment.

This text-book is based on the concept of transfer phenomena – irreversible processes which are important from the point of view of viability of living organisms; the spatial transfer of physical values such as entropy, mass, energy, momentum, electric charges in the environment occurs due to these phenomena. Such an approach makes it possible to unite all biophysical processes that characterise the interaction of living organisms with the environment.

This text-book is intended for the students of Environmental Sciences. It will be useful for those students whose native language is not English and who want to improve the knowledge of professional English terminology that will make it possible to better understand modern literature, take a more active role in scientific missions abroad, get into contact with foreign colleagues, and enhance attendance at international conferences, symposiums, seminars, etc.

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Part I. PHYSICAL SURROUNDINGS OF LIVING ORGANISMS

1. MECHANICAL FACTORS OF THE ENVIRONMENT

1.1. PRESSURE

Definition of pressure

The *pressure* is a physical quantity which characterizes the intensity of normal (perpendicular to the surface) force with which one body acts on the surface of another. If the force exhibits a uniform distribution along the surface, the pressure is determined as the ratio of force to area:

$$p = \frac{F}{S} \qquad (1.1)$$

where F is the magnitude of the normal force on the surface and S is the area of this surface.

If the pressure is not uniform across the surface, the following expression defines the pressure at a specific point:

$$p = \sum_{\Delta S \to 0} \frac{\Delta F}{\Delta S} = \frac{dF}{dS} \qquad (1.2)$$

The SI unit for pressure is the *Pascal* (1 N/m^2 = 1 Pa). The following pressure units are also used:

	pascal (Pa)	bar (bar)	technical atmosphere (at)	atmosphere (atm)	torr (mmHg)	pound-force per square inch (psi)
1 Pa	=1 N/m^2	10^{-5}	$1.0197 \cdot 10^{-5}$	$9.8692 \cdot 10^{-6}$	$7.5006 \cdot 10^{-3}$	$145.04 \cdot 10^{-6}$
1 bar	100000	=10^6dyn/cm^2	1.0197	0.98692	750.06	14.504
1 at	98066.5	0.980665	=1 kgf/cm^2	0.96784	735.56	14.223
1 atm	101325	1.01325	1.0332	=1 atm	760	14.696
1 torr	133.322	$1.3332 \cdot 10^{-3}$	$1.3595 \cdot 10^{-3}$	$1.3158 \cdot 10^{-3}$	=1 mmHg	$19.337 \cdot 10^{-3}$
1 psi	6894.76	$68.948 \cdot 10^{-3}$	$70.307 \cdot 10^{-3}$	$68.046 \cdot 10^{-3}$	51.715	=1 lbf/in^2

Variations in Pressure with Depth

The pressure at depth (d) in opened vessel is determined by:

$$p = p_A + \rho g d \qquad (1.3)$$

where p_A ($\approx 1.01 \cdot 10^5$ Pa) is the atmospheric pressure; ρ is the density of the fluid; g is the acceleration due to gravity.

Example. Calculate the pressure at the bottom of the Marianas Trench (depth 11043 m). Assume the density of water $\rho = 1 \cdot 10^3$ kg/m^3 and atmospheric pressure $p_a = 1.01 \cdot 10^5$ Pa.

Solution. Using formula (1.3), the pressure is equal to:

$p = p_A + \rho g d = 1.01 \cdot 10^5$ Pa $+ (1.0 \cdot 10^3$ kg/m^3)(9.8 m/s^2)(11043 m) = 109 MPa.

Physiological effects of increased pressure on human health

The representatives of some professions, such as Arabian sponge divers, Australian pearl divers, Japanese and Korean Ama, dive into the sea without any special equipment.

Diver. From www.deepseaimages.com

Japanese Ama Diver. From http://en.wikipedia.org/wiki/Ama_divers

There are such kind of extreme sport as competitive apnea in which sportsmen attempt to attain great depths, times or distances on a single breath without any special equipment.

Official world records in underwater diving as of June 2007 are:

free immersion (in which the athlete uses the guideline to pull him or herself down to depth and back to the surface)

women: Nataliya Molchanova (Russia) – 80 metres;

men: Martin Štěpánek (Czech Republic)) – 106 metres;

no limits (is a record discipline that allows the athlete to use any means of breath-hold diving to depth and return to the surface as long as a guideline is used to measure the distance)

women: Tanya Streeter (Cauman Islands) – 160 metres;

men: Herbert Nitsch (Austria) – 214 metres.

When a diver ascends rapidly without any decompression stops after deep or long dive he is exposed to certain dangerous consequences:

Pneumotorax. When divers descend, they are sensitive to the surrounding water pressure which increases at a rate of one atmosphere for each 10 m in descent (i.e., Δp = 1 atm for Δd = 10 m). The pressure of the surrounding water is transmitted to all internal parts of the body and a state of pressure equilibrium is established where the internal pressure of the body is equal to the surrounding pressure. During ascent and descent the diver must support the pressure of air in his lungs the same as that of the surrounding water. For example, if the diver goes to 30 m underwater by holding a full breath of air, he would have 4 atm of pressure in his lungs according to Equation (1.3). When ascending, the pressure at the water surface is 1 atm, while the pressure in his lungs would be 3 atm. This pressure difference can lead to the rupture of his lungs, a phenomenon termed *pneumotorax*.

Effect of Nitrogen. The air we breathe contains 79% of nitrogen; as a consequence, our blood is full of dissolved nitrogen.

Decompression sickness (*the bends*, or *caisson disease*) is the name given to a variety of symptoms suffered by a person exposed to a reduction in the pressure surrounding their body. This sickness occurs during fast ascent of the diver from the depth without decompression stops.

According to *Henry's Law*, the amount of dissolved gas in a liquid at constant temperature is directly proportional to the partial pressure of the gas. Liquids which are under high pressure can dissolve more gas than liquids which are under low pressure; nitrogen is absorbed into the tissues of the body in higher concentrations than normal. If a diver ascends too quickly, the excess dissolved nitrogen in the blood will come back out of solution and form gas bubbles in the blood vessels; and that these bubbles will block blood flow to certain tissues and vital organs. The diver will suffer the effects of a painful disease called the *caisson disease* (from the French word "*caisse",* a chest) or the *bends*, which leads to fatigue, pain in the joints, rashes or itchy patches, dizziness, nausea, disorientation, numbness, neuralgic pains, sensory system failure, paralysis, and death.

The formation of the gas bubbles in the blood vessels leads to the rupture or obstruction of blood vessels; a disease called *gas embolism.* It is accompanied by an immediate loss of consciousness or convulsions. If gas embolism takes place in the blood vessels of the brain or the coronary circulation, the gas bubbles can break the flow of oxygen-rich blood to the brain and vital organs and result in death.

Oxygen Poisoning. When a diver is underwater, the tissues use a certain amount of dissolved oxygen from hemoglobin, the oxygen transport protein found in the erythrocytes of the blood. At sufficient depth, the pressure increases to the point that oxygen binding and transport by hemoglobin is prevented and the tissues remain saturated. The high concentration of oxygen leads to the damage of the cells, formation of superoxide (result of the reaction of oxygen with some metals) which destroys the double bonds in organic systems, and free radicals that disturb DNA and the functions of cell membranes.

The symptoms of oxygen toxicity are convulsions and unconsciousness.

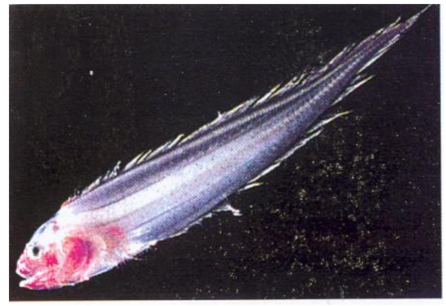
Hypercapnia (from the Greek *hyper* – "above" and *kapnos* – "smoke"), or *CO_2 Poisoning,* is a condition where there is too much carbon dioxide (CO_2) in the blood. Carbon dioxide as a gaseous product of the body's metabolism that is normally expelled through the lungs. But if the diver is not exhaling completely CO_2 through the various vessels such as snorkel, diving mask or helmet, he re-inhales this gas from these vessels. The breakage of the system of gas cleaning or over-exercising of the diver can lead to CO_2 poisoning also.

Symptoms of hypercapnia includes flushed skin, raised pulse and blood pressure, muscle twitches; severe hypercapnia is accompanied with disorientation, state of panic, convulsions, lethargy, narcosis, unconsciousness and even by death.

Adaptation of Diving Animals to Depth

The deep-sea environment is characterized by a high hydrostatic pressures which increases by approximately 1 MPa (10^6 Pa) for every 100 m in depth. There are a number of diving marine animals which can live under the pressure of tens or even hundreds of atmospheres. The depth range for different marine animals is: 200-300 m (maximal depth is about 900 m) – fur seals, *Callorhinus*; 457 m – Weddell seal, *Leptonychotes weddelli*; 500-2000 m – deep-sea eel, *Synaphobranchus kaupi*; greater than 500 m – emperor penguin, *Aptenodytes fosteri*; below 1500 meters –northern elephant seal, *Mirounga angustirostris*; 2000-3000 m – sperm whale, *Physeter catodon*; 7250 – sea urchin, *Echinoidea*; 7360 m – sea star, *Asteroidea*; 8370 m – cuskeel fish, *Ophidiidae*; 10190 – sea cucumber, *Holothurioidea*.

Sperm Whale. From http://www.fotosearch.com/UNY456/u



Abyssobrotula galatheae, holds the depth record among fish at 8,370 meters in the Puerto Rico Trench

The duration of diving of these animals varies also: the emperor penguin is staying submerged for about 12 minutes; in shallower dives, an emperor penguin may stay submerged even longer, over 20 minutes; sea lions and seals can stay underwater for 30 minutes or longer; sperm whales are capable of very long dives more than one hour.

Jacques Piccard, studying extreme marine depths, observed through the illuminator of his bathyscaph shrimp and fish at a depth of 10912 m. Some invertebrates and bacteria have been found near the bottom of the Marianas Trench (depth 11043 m, pressure of about 110 MPa).

What biological mechanisms allow these animals to function at such depths?

Marine mammals demonstrate so-called *mammalian diving reflex* which means the regime of oxygen saving and includes:

Bradycardia – reduced heart rate. Diving animals are able to decrease their heart rate during the dive, relative to that at the surface. For instance, a muskrat has about 320 heart beats per minute before diving but only 34 beats per minute at depth; on land, seals have a heart rate of 107 beats per minute, but at depth their pulse decreases to 68 beats per minute.

Increased peripherical vasoconstriction – a decrease in blood flow to the extremities in order to increase the supply of blood and oxygen to the vital organs, especially the heart and the brain; such a heart-brain circuit can allow the mammal to conserve oxygen.

Blood shift – transfer of blood plasma to the thoracic cavity that make it possible to avoid the collapse of the lungs during diving. It is necessary to mention the ability of these animals to exhale before the diving: for example, cetaceans can exhale about 88 % of their lung air with a single breathe while humans can only exhale only about 12 %. This causes the lungs of diving marine animals to reduce the volume quickly preventing atmospheric gases (nitrogen, oxygen) from entering the bloodstream. Most of the oxygen in diving animals is distributed in the blood and muscle while the lungs contain small (less than 5%) amount of the oxygen.

One of the main adaptation mechanism of diving animals can be explained with their ability to distribute and store oxygen. The animals breathe, take oxygen from the air and transport it into the lungs; then the oxygen is transferred to the blood which contains the haemoglobin – the molecule that is located in erythrocytes and carries oxygen through all the organism. The diving animals can use oxygen from blood which has a high volume and hematocrit (a number of blood cells). As a consequence, the skeletal muscle tissue of the animals contains about 47% of the overall body oxygen. The large amount of hemoglobin in the muscles is responsible for their deep-red color. The store of oxygen is realised due to myoglobin – complex protein of muscles.

The main function of myoglobin is to bind oxygen. Myoglobin has a higher affinity for oxygen than does hemoglobin. When blood passes through muscle, oxygen is transferred from the blood to the muscle. The amount of myoglobin in muscles of diving animals is from 3 to 10 times higher than in the muscles of terrestrial animals. That's why the diving animals can store more oxygen than other animals.

People have a total oxygen capacity of 20 milliliters per kilogram of body mass while the diving animals are characterised with more higher oxygen capacity – 55 and 87 milliliters of oxygen per kilogram of body mass in penguins and Weddell seals correspondingly.

There is a remarkable ability of deep-diving sea animals to change the volume of their lungs. They have fully inflated lungs at the surface; the lungs begin to collapse during the diving. At least, the lungs collapse completely at the depth and any gas exchange between them and the blood is brings to a stop.

Atmospheric Pressure

Atmospheric pressure is defined as the weight of the column of atmospheric air which acts on the unit of surface area. This air is a mixture of gases, solid and liquid particles. As a whole, the atmospheric pressure depends on the height; it is characterised also with horizontal distribution. The density and temperature of the atmospheric air depend on the height too (Table 1.1).

1.1. Dependence of the atmospheric density and temperature on the height

Height *z*, km	Density ρ, kg/m^3	Temperature, *t* ^{0}C
0	1.225	15.00
2	1.007	2.00
4	0.909	–4.49
6	0.660	–23.96
8	0.526	–36.94
10	0.414	–49.90
12	0.312	–56.50
14	0.228	–56.50
16	0.166	–56.50
18	0.122	–56.50
20	0.089	–56.50
22	0.065	–54.58
24	0.047	–52.59
26	0.034	–50.61
28	0.025	–48.62
30	0.018	–46.64

Note: Pay attention that atmospheric temperature is changing with the height by unexpected way: it is decreasing up to 12 ^{0}C; it is constant in the region 12–20 ^{0}C; it is increasing from 20 ^{0}C tp 30 ^{0}C. The explanation of such a behaviour of the atmospheric temperature you can find in the section "Atmospheric Temperature".

Variation of Pressure with Height

The idea of uniform distribution in volume of the atmospheric molecules is erroneous. These molecules are in the gravitational field of the Earth; in addition, there is the effect of thermal motion of these molecules on their spatial distribution. The combined action of the gravitational field and thermal motion leads to the state which is characterised by decreasing of concentration and pressure of gas with the height.

The variation of pressure with height is given as:

$$p_A(z) = p_A(0)exp[-(gM_A/RT_A)]z \qquad (1.4)$$

where $p_A(0)$ is the pressure at sea level where the height (z) is 0 (i.e., z_0); g – is the acceleration due to gravity; M_A – the molar mass of the gas (M_A = 0.029 kg/mol for air); R – the universal gas constant; T_A – the absolute temperature.

This equation is known as the *Barometric Formula* and indicates an exponential decrease in pressure with increasing elevation.

Example. Find the atmospheric pressure at 5000 m. To calculate the height (z_0) of air at T = 0 ^{0}C and an average molecular mass (M_A) of $47.3\cdot10^{-24}$ g:

$$z_0 = \left(\frac{kT}{M_A g}\right) = \left(\frac{1.38\cdot10^{-16}\cdot273}{47.3\cdot10^{-24}\cdot980}\right) = 8150 \text{ m}$$

Thus it is possible to obtain for practical purposes a suitable estimation of the variation in pressure with height above the Earth:

$$p = 760e^{-z/8150} \text{ mm Hg}$$

Solution. The atmospheric pressure can be find as:

$$p = 760e^{-z/8150} \text{ mm Hg} = 760\ e^{-5000/8150} = 760\ e^{-0.6135} = 760\cdot0.5415 = 411 \text{ mm Hg.}$$

Physiological Effects of Decreased Pressure on Human Health

The people who reach high altitude without special equipment (mountain-climbers , balloonists, or persons living at high altitudes) are exposed to *altitude sickness* (*mountain sickness, altitude illness*). Let's consider different effects of low atmospheric pressure at different altitudes.

1500 m. The first organ which can suffer from low air pressure is the retina of the eye; at these altitudes the brain demonstrates degradations which are displayed in night vision. Scales of instruments, maps and other documents are easily misread and misinterpreted during night at this altitude.

2500 m. Maximum work capacity decreases roughly 1 % for each 100 m above 2500 m.

3000 m. The presence at this altitude is characterised with the drop of the blood saturation to 90 % and degradation of night vision by 12-15 %. The euphoria impedes the real estimation of the human activity. A physical hypoxia is beginning from this altitude. The first signs of altitude sickness at this altitude are seen as slight changes in pulse and breathing rate, *anorexia* (an eating disorder due to loss of appetite), and a loss of body weight (about 1 kg in a week) due to decreased thirst and increased urine volume. These alterations increase substantially in the 3000-4000 m altitude range.

4200 m. This altitude is accompanied with the decrease of blood oxygen saturation to a 85 % that provokes the serious degradation in vision, judgement, muscular control, memory and thought. The primary symptoms of mountain sickness from this altitude are *dyspnea* (difficult breathing), *tachycardia* (a form of cardiac arrhythmia which refers to a rapid beating of the heart; the heart rate in excess of 100 beats per minute), *malaise* (a feeling of general discomfort or uneasiness, vague body discomfort), *nausea* (the feeling that one is about to vomit) and *vomiting* (the forceful expulsion of the contents of the stomach through the mouth), *insomnia* (a sleep disorder, an inability to sleep) and *lassitude* (a state or feeling of weariness, diminished energy, or listlessness).

4800 m. Blood oxygen saturation drops to 79 %. There are serious variations of emotional state – euphoria, bellicosity, irritation.

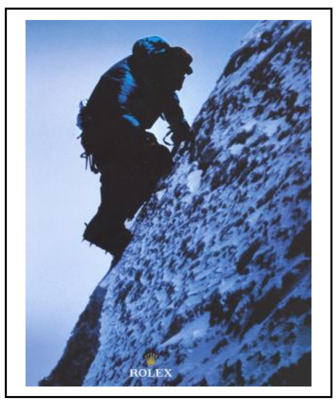
5400 m. Blood oxygen saturation continues to drop up to 71 %. The brain is suffering.

6000 m. Consciousness after 5-15 minutes of presence at this altitude and the death as result of more prolonged exposure.

7500 m. Critical drop of blood oxygen saturation leads to death.

Thus, the physiological effects that are caused by decreased air pressure and low oxygen supply are called *hypoxia* which makes a transition from *compensated hypoxia* (measurable increase in heartbeat and breathing rate, but only slight loss of efficiency in performing complex tasks) at the altitudes between 3150-4750 m to *manifest hypoxia* (the respiratory and heart rates markedly increase, loss of critical judgment and muscular control, dulling of the senses, and variation of emotional state from lethargy to euphoria and even hallucinations) between 4570-6100 m and *critical hypoxia* (rapid loss of neuromuscular control, consciousness, cessation of respiration and finally death) at 6100-7260 m.

The mechanism of altitude sickness can be explained by local vasodilation (broadening) of cerebral blood vessels in response to hypoxia, resulting in greater blood flow and, consequently, greater capillary pressures or by general vasoconstriction (narrowing) in the pulmonary circulation (normally a response to regional ventilation) which, with constant or increased cardiac output, can also leads to increases in capillary pressures.



Physiological Effects of Altitude on Animals

A number of animals demonstrate the ability of acclimatisation and adaptation to the low oxygen conditions in high altitude areas.

The Lake Titicaca *frog*, for example, lives at an altitude of 3812 m. The adaptation mechanisms of this animal is realised by extensive skin folds that make it possible to provide gas exchange; high level of hematocrit and erythrocyte concentration leads to thev increasing transport of oxygen.

Turtles are characterised by the greatest tolerance to hypoxia due to their capacity to anaserobic metabolism, low metabolic rate, possibility to shunt of blood away from the lungs when their ventilation is not possible.

Mules are used at Aucanquilcha, a base camp for the International High Altitude Expedition, as a transport means in the 5250-6000 m altitude range. The animals demonstrate the ability to accurately assess their capacity for work and refuse to be pushed beyond a safe limit.

Other animals at high altitudes are the *vicuna* (5000-6000 m), *domestic sheep* (up to 5250 m), and *horses* (up to 4600 m). The animals that are living in high altitude habitat show the elevated erythrocyte count and haemoglobin level as a rule. Those animals who are transported to high altitude areas demonstrate hematocrit increase.

Birds, which are flying and migrating over the Tibetian Plateau and Himalayan mountains, however, hold the high altitude records: *condors* (7600 m), *geese* (8534 m), *chough* (9000 m) and *griffon vulture* (11278 m). The life of these birds at high altitudes leads also to structural changes of hemoglobin that provide their capacity to fly at such great heights.

Effects of Altitude on the Plants

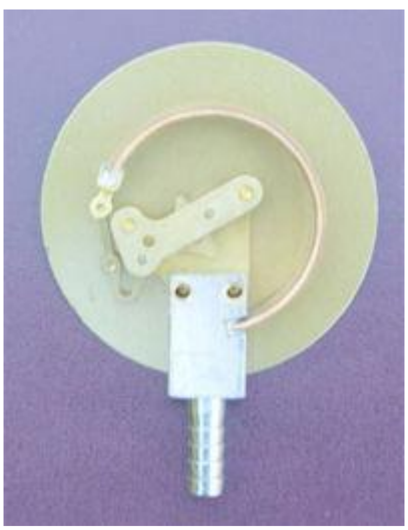
Altitudinal variation of climate induces morphological and physiological changes in plants and their canopy architecture. Often the plants maintain a compact or dwarf form with small, narrow or densely pubescent leaves. The ecological zone between 3230 and 3660 m is called an *alpine* area. Here it is possible to find considerable changes in quantitative and qualitative characteristics of the fauna. In addition, there are certain changes in climatic conditions that are related to the effects of pressure, wind, humidity and precipitation, temperature, radiation and gas exchange, which in turn, also modify the fauna.

Measurement of Atmospheric Pressure

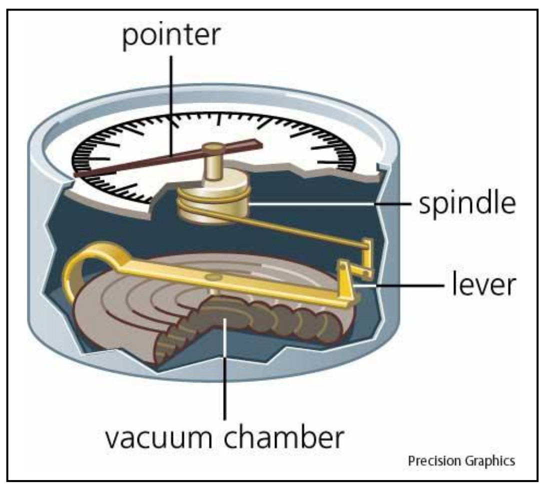
A *barometer* is an instrument which is used to measure changes in atmospheric pressure. There are two type of mechanical barometers: *aneroid* (from French anéroïde: Greek a – *without* and late Greek nron – *water*) and the *Bourdon tube*.

The first type has a flattened curved tube that straightens under the changes of atmospheric pressure, allowing the force to be measured. The motion of the curved tube is transferred to a gear train which is connected to an indicating needle.

The second type of instrument consists of an aneroid capsule – a thin (0.2 mm), disk-shaped box or capsule, usually metallic, which is partially evacuated of gas, and is restrained from collapsing by an external or internal spring. The deflection of the spring is proportional to the difference between the internal and external pressures. Magnification of the aneroid is obtained by connecting capsules in series (up to 14 capsules).



Barometer of Bourdon tube
From
http://en.wikipedia.org/wiki/Manometer



Principle of action of barometer-aneroid
From
www.stuffintheair.com

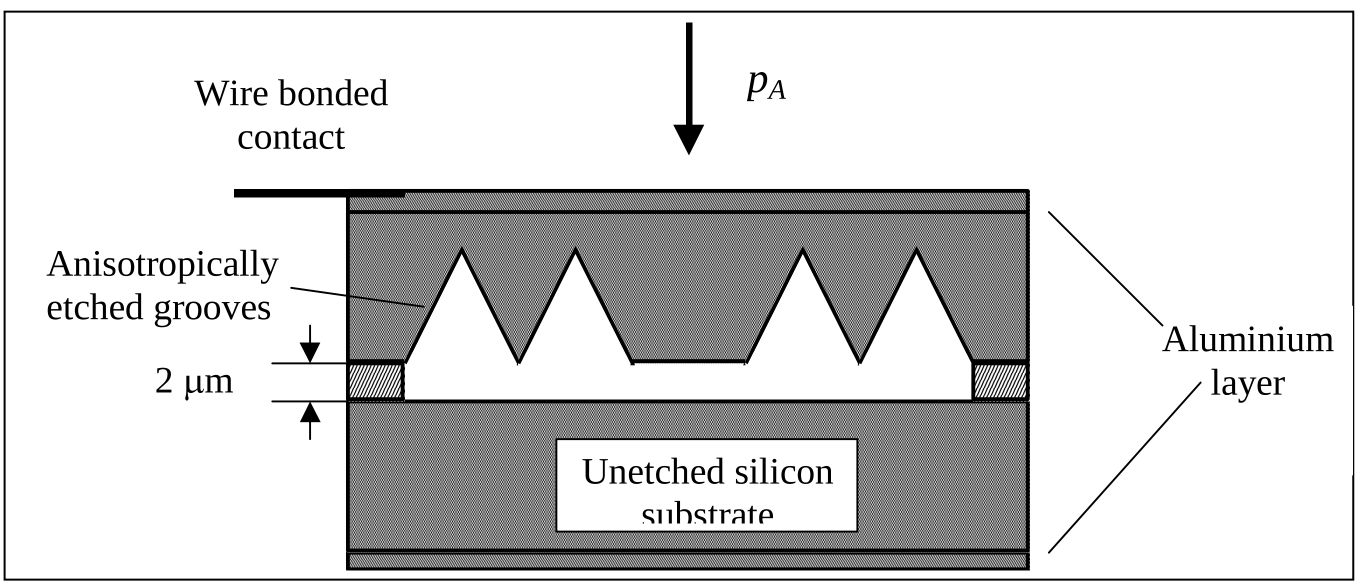
Barograph is a device for recording automatically the changes of atmospheric pressure over a period of time.

Barograph

The advantage of aneroid is its compactness, mechanical strength, transportability. Aneroid gauges are not dependent on the contamination of the air. These devices can be used in systems of automatized measurement of atmospheric pressure as soon as deflection of curved tube or aneroid capsules can be easily transferred into electrical signal.

*Digital Barometric Pressure Sensor***.** The fabrication of such a device can be possible due to the modern technologies. This silicon capacitive absolute pressure sensor consists of two silicon substrates fusion bonded together with a silicon dioxide (SiO_2) layer sandwiched between them. The silicon substrates form either the mechanical sensor or capacitor electrodes. The top silicon substrate has been etched to form corrugations in the diaphragm to define the behaviour of the diaphragm under pressure. The thickness of the SiO_2 layer determines the gap between the electrodes and correspondingly the base capacitance of the device.

Principle of operation of device is based on the response of capacitive absolute pressure sensor on the applied atmospheric pressure which changes the distance between silicon substrates, that form the electrodes of capacitor, and corresponding the value of capacitance.



Digital Barometric Pressure Sensor PTB210
Vaisala, Finland

Measurement range	50 ... 1100 hPa or 500 ... 1100 hPa
Serial output	
Accuracy at +20 °C	
500 ... 1100 hPa	
Class A	±0.15 hPa
Class B	±0.20 hPa
50 ... 1100 hPa	±0.35 hPa
Long-term stability	
500 ... 1100 hPa	
Class A	±0.1 hPa / year
Class B	±0.1 hPa / year
50 ... 1100 hPa	±0.2 hPa / year
Analog output	
Accuracy at +20 °C	±0.30 hPa
Sensor	Vaisala BAROCAP®

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WIND

Definition of Wind

Wind is the motion of air relative to the ground. Wind is a vector quantity that is characterised by either numerical or directional properties.

The Forces that induce the Wind

Wind is induced by a series of forces:

1) The *pressure gradient force* arises from the difference in pressure over proper distance and tends to impel air motion from areas of high to areas of low pressure. It is related to spatial variations in air temperature or *temperature gradients* (f.e., a wind from the sea that develops over land near coasts; the sea is warmed by the sun to a greater depth than the land).

2) *Gravity*, which induces the acceleration of the air downward at a rate 9.8 m/s^2. This force is directed always perpendicular to the Earth's surface and doesn't participate in formation of horizontal winds.

3) *Friction*, is the resistance that the air particles encounters during the contact with ground surface; it is defined as

$$F = -\mu\upsilon, \qquad (1.5)$$

where μ – coefficient of friction which depends on the type of surface; υ – wind velocity. Force of friction is proportional to the velocity of wind and has an opposite direction.

4) *Coriolis force*, induced by the rotation of the earth; it deflects the wind to the right of its direction in the northern hemisphere and to the left – in the southern hemisphere. Coriolis force is proportional to the wind speed and is expressed by

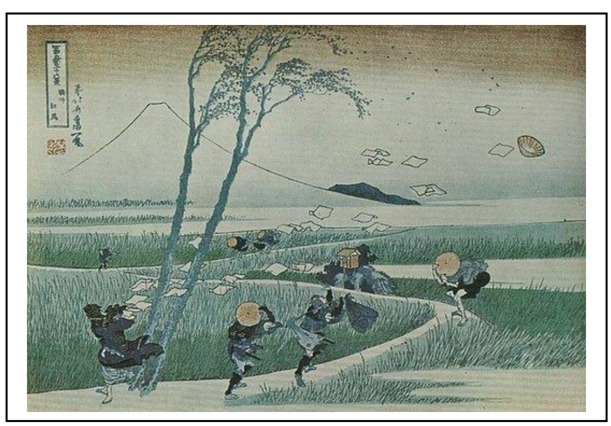
$$F_k = 2\rho\upsilon\omega\sin\varphi, \qquad (1.6)$$

where ρ – the density of air; υ – wind velocity; ω – rate of rotation of the earth ($7{,}3\cdot10^{-5}$ rad/s); φ – latitude.

5) *Centripetal Force*, the force that is directed inward the curved path. It causes a change in the direction of the wind but not the change in velocity.

Katsushika HOKUSAI
(1760–1849)

"Ejiri in Suruga Province"
(1830-5)



Parameters of Wind

Winds are characterised with their speed, direction and gusty.

Wind speed is measured in meter per second (m/s), or kilometers per hour (km/h, kph), miles per hour (m/h, mph), sometimes – in knots (nautical miles per hour = 1 international knot = 1.852 kilometres per hour exactly).

These units and conversion of units are summarised in Table 1.2.

1.2. Units of wind speed

m/s	*knots*	*km/h*	*ft/s*	*mph*
1.0	1.9	3.6	3.3	2.2
0.5	1.0	1.9	1.7	1.2
0.3	0.5	1.0	0.9	0.6
0.3	0.6	1.1	1.0	0.7
0.4	0.9	1.6	1.5	1.0

Intense winds often have special names, such as *gales*, *hurricanes*, *tornados*, and *typhoons*.

A *gale* is a very strong wind which has a speed from 51 to 102 km/h (32 to 63 mph). These values of speed correspond to force 7 to 10 on the Beaufort scale.

A *hurricane* is a tropical storm with winds from 119 to 257 km/h (or 74 to 160 mph) that takes place usually in the equatorial regions of the Atlantic Ocean Sea or eastern regions of the Pacific Ocean and is accompanied by thunder, rain and flooding. These values of speed correspond to force 12 on the Beaufort scale.

A *tornado* is a violently rotating column of air ranging in width from a several meters to more than a kilometer which is characterized by destructively high speeds (up to 177 km/h or 110 mph) and is in contact with a cumulonimbus (that is involved in thunderstorms) cloud; it travels a few several kilometers before dissipating. Tornado occurs most of all in the United States.

A *typhoon* is a violent tropical cyclone occurring in the western Pacific or Indian oceans.

Wind speed is estimated by the *Beaufort Scale* (Table 1.3). It was devised in 1805 by Sir Francis Beaufort and is based on the estimation of wind strength without instruments but on the visual observation only of the environmental effects which were produced by wind.

1.3. Beaufort Scale

Force	Name	*m/s*	*knotd*	*km/h*	Effects (L-land; S-sea)
0	Calm	0.0-0.2	< 1	< 1	**L-** Smoke rises vertically **W-** Like a mirror

1	Light air	0.3-1.5	1-3	1-5	**L-** Rising smoke drifts **W-** Small ripples
2	Light breeze	1.6-3.3	4-6	6-11	**L-** Leaves rustle **W-** Small wavelets, wind fills sail
3	Gentle breeze	3.4-5.4	7-10	12-19	**L-** Light flags extend **W-** Large wavelets, sailboats heel
4	Moderate breeze	5.5-7.9	11-16	20-28	**L-** Moves thin branches **W-** Working breeze, sailboats at hull speed
5	Freash breeze	8.0-10.7	17-21	29-38	**L-** Small trees sway **W-** Numerous whitecaps, time to shorten sails
6	Strong breeze	10.8-13.8	22-27	39-49	**L-** Large tree branches move **W-** Whitecaps everywhere, sailboats head ashore, large waves
7	Near gale	13.9-17.1	28-33	50-61	**L-** Large trees begin to sway **W-** Much bigger waves, some foam, sailboats at harbor
8	Gale	17.2-20.7	34-40	62-74	**L-** Small branches are broken from trees **W-** Foam in well marked streaks, larger waves, edges of crests break off
9	Strong gale	20.8-24.4	41-47	75-88	**L-** Slight damage occurs to buildings **W-** High waves, dense spray, visibility affected
10	Storm	24.5-28.4	48-55	89-102	**L-** Large trees

					uprooted, considerable building damage **W**- Very high waves, heavy sea roll, surface white with spray and foam, visibility impaired
11	Violent storm	28.5-32,6	56-63	103-117	**L**- Extensive widespread damage **W**-Exceptionally high waves, small to medium ships obscured, visibility poor
12	Hurricane	> 32.7	> 64	> 118	**L**- Extreme destruction **W**- Waves over 14 m, air filled with foam and spray, visibility restricted

The Saffir-Simpson Hurricane Scale (Table 1.4) is used for estimation of the hurricane's intensity. It is based on 5-level rating of the potential property damage and flooding which are observed along the coast. This scale was designed by Herbert Saffir and Robert Simpson, USA.

1.4. The Saffir-Simpson Hurricane Scale

Category	Wind speed, km/h	Effects
1 (minimal)	119-153	Damage primarily to unanchored mobile homes, shrubbery, and trees. Some damage to poorly constructed signs. Also, some coastal road flooding and minor pier damage.
2 (moderate)	154-177	Some roofing material, door, and window damage of buildings. Considerable damage to shrubbery and trees with some trees blown down. Considerable damage to mobile homes, poorly constructed signs, and piers. Coastal and low-lying escape routes flood 2-4 hours before arrival of the hurricane center.
3 (extensive)	178-279	Some structural damage to small residences and utility buildings with a minor amount of curtainwall failures. Damage to shrubbery and trees with foliage blown off trees and large tress blown down. Mobile homes and poorly constructed signs are destroyed. Low-lying escape routes are cut by rising water 3-5

		hours before arrival of the hurricane center. Flooding near the coast destroys smaller structures with larger structures damaged by battering of floating debris. Terrain continuously lower than 5 ft above mean sea level may be flooded inland 8 miles (13 km) or more. Evacuation of low-lying residences with several blocks of the shoreline may be required.
4 (extreme)	210-249	More extensive curtainwall failures with some complete roof structure failures on small residences. Shrubs, trees, and all signs are blown down. Complete destruction of mobile homes. Extensive damage to doors and windows. Low-lying escape routes may be cut by rising water 3-5 hours before arrival of the hurricane center. Major damage to lower floors of structures near the shore. Terrain lower than 10 ft above sea level may be flooded requiring massive evacuation of residential areas as far inland as 6 miles (10 km).
5 (catastrophic)	> 249	Complete roof failure on many residences and industrial buildings. Some complete building failures with small utility buildings blown over or away. All shrubs, trees, and signs blown down. Complete destructon of mobile homes. Severe and extensive window and door damage. Low-lying escape routes are cut by rising water 3-5 hours before arrival of the hurricane center. Major damage to lower floors of all structures located less than 15 ft above sea level and within 500 yards of the shoreline. Massive evacuation of residential areas on low ground within 5-10 miles (8-16 km) of the shoreline may be required.

The wind speed reaches 65 m/s in the Antarctic, 110 m/s – in the tropics. The wind speed depends on the height h over the sea level: υ = 5 m/s (h = 20 m); υ = 20-25 m/s (h = 300 m); υ = 60-80 m/s (h = 10-17 km). The highest surface wind speed ever officially recorded is 372 km/h (231 m/h) during a gust at the Mount Washington Observatory in the U.S.A. on 12th April 1934.

Wind direction is the direction from which the wind is blowing. It is usually reported in cardinal directions or in azimuth degrees (Table 1.5).

1.5. Compass points

N	Compass point	Abbr.	Traditional wind point	True heading
1	**North**	N	*Tramontana*	0.00°
2	North by east	NbE		11.25°
3	North-northeast	NNE		22.50°
4	Northeast by north	NEbN		33.75°
5	**Northeast**	NE	*Greco Bora*	45.00°
6	Northeast by east	NEbE		56.25°
7	East-northeast	ENE		67.50°
8	East by north	EbN		78.75°
9	**East**	E	*Levante*	90.00°
10	East by south	EbS		101.25°
11	East-southeast	ESE		112.50°
12	Southeast by east	SEbE		123.75°
13	**Southeast**	SE	*Sirocco*	135.00°
14	Southeast by south	SEbS		146.25°
15	South-southeast	SSE		157.50°
16	South by east	SbE		168.75°
17	**South**	S	*Ostro*	180.00°
18	South by west	SbW		191.25°
19	South-southwest	SSW		202.50°
20	Southwest by south	SWbS		213.75°
21	**Southwest**	SW	*Libeccio*	225.00°
22	Southwest by west	SWbW		236.25°
23	West-southwest	WSW		247.50°
24	West by south	WbS		258.75°
25	**West**	W	*Ponente*	270.00°

26 West by north	WbN		281.25°
27 West-northwest	WNW		292.50°
28 Northwest by west	NWbW		303.75°
29 Northwest	NW	*Maestro*	315.00°
30 Northwest by north	NWbN		326.25°
31 North-northwest	NNW		337.50°
32 North by west	NbW		348.75°

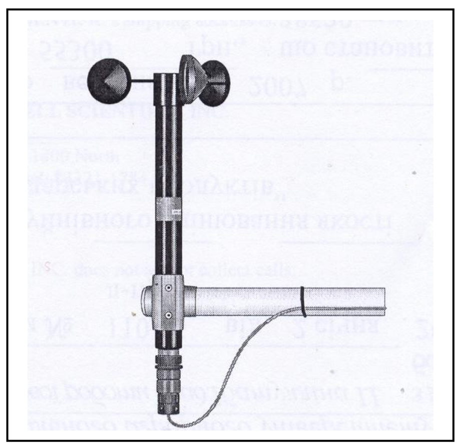
Measurement of Wind Parameters

Anemometer (from the Greek *anemos* – wind) is a device for measuring wind speed either directly, through estimation of rotation of cups or windmill, or via measuring the propagation speed of ultrasound or light signals.

The *cup anemometer* consists three or four semispherical cups which are mounted one on each end of a horizontal arms, which lie at equal angles to each other. The axis of rotation of the cups is vertical. The velocity of rotation of the cups under flowing wind is proportional to the wind speed.

Model 014A Met One Wind Speed Sensor
Campbell Scientific, Inc.

Specifications
Threshold
0.45 m/s (1mph)
Calibrated Range
0-45 m/s (0-100 mph)
Gust Survival
0-53 m/s (0-120 mph)
Accuracy
1.5 % or 0.11 m/s (0.25 mph)
Temperature Range
50 ^{0}C - +70 ^{0}C



Windmill anemometer (aerovane) combines a propeller and a tail on the same axis to obtain accurate and precise wind speed and direction of the air motion is always the same. The axis of rotation of the a propeller is horizontal. Such an anemometer can be conjugated with a rotating vane to estimate wind speed and direction simultaneously.

Hot-wire anemometer consists of a thin (about several micrometers) wire which is heated by passing electric current through it up to some temperature above the surroundings. Wind flowing provides a cooling of the wire. The measurement of the resistance of the wire which depends strongly on its temperature makes it possible to estimate the wind speed. Hot-wire anemometer is more sensitive than the cup anemometer.

Sonic anemometer is based on the dependence of propagation speed of ultrasound in air on the direction of wind. It consists usually three pairs of transducers; the path length between them is 10-50 cm. Each pair of transducers includes a generator and receiver of ultrasound and oriented at different angles to each other. The utrasound propagates more quickly in the wind direction and more slowly in the opposite direction.

Ultrasonic anemometer detects the phase shifting of sound which depends on the orientation of the transducers relative to the wind direction. The advantage of sonic anemometers is their insensitivity to icing.

Three-dimensional Sonic
anemometer-thermometer
DA-600-3TV, TR-61C, Kaijo
Range 0-30 m/s
Resolution 0.005 m/s

Laser Doppler anemometer is based on the detection of the *Doppler effect*. Let's discuss the source of light and a receiver which detects this light. When either the source or the receiver of a propagating light wave moves, there is usually a change in frequency called the *Doppler* *shift.* Such a shift can be used to determine the velocity of the target along the line to it, which is to say its *approach velocity*. If the transmitter generates a frequency of f_0, the velocity of the sound is υ_s, and the approach velocity is a much smaller value (υ_a), the received frequency is approximated by:

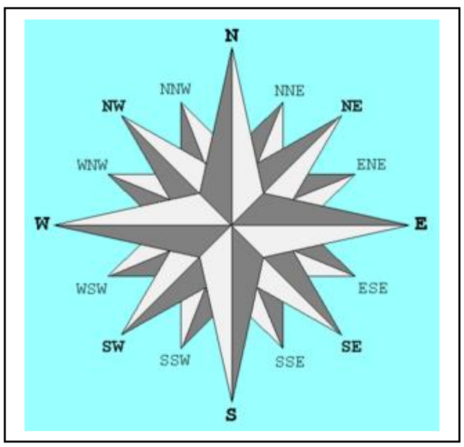
$$f = f_0 \left(1 + \frac{2\upsilon_a}{\upsilon_s}\right) \qquad (1.7)$$

The Doppler frequency shift is proportional to the approach velocity:

$$\Delta f = f - f_0 = \frac{2 f_0}{\upsilon_s}\upsilon_a . \qquad (1.8)$$

When the laser beam irradiates the air molecules which are in motion relative to the ground, the reflected beam acquires a Doppler shift Δf which depends on the wind speed. These devices can be used in during the remote sensing of upper-air wind speed measurements.

Wind vane<u>**:**</u> an instrument used to monitor wind direction by always pointing into the wind. Wind direction is always designated as the direction from which the wind blows. Measured clockwise from the true north, an easterly wind is designated as 90^0, a southerly wind as 180, a westerly wind as 270^0, and a northerly wind as 360^0. The wind recorded as 0^0 is only at calm conditions.



Wind sock represents a striped open bag of conical shape which indicates wind direction and relative speed at airports.

Effect of Wind on Living Organisms

The ability of flying insects to demonstrate the responsive movement toward or away from such an external stimulus as wind is called *anemotaxis*.

Flying insects attempts to fly directly along wind direction when they are in contact with a pheromone plume and to fly back and forth perpendicular the wind when this contact is lost. *Pheromones* (from Greek *pherein* – to carry or transfer, and *hormōn* – to excite or stimulate) are the molecules that are transported by wind and used for communications between animals. In addition, flying insects can control their position by observing the ground surface below; if the ground is moving directly underneath insect doesn't change orientation; if the ground moves to left the insect turns to left also to keep direct related to wind orientation.

The beetles can provide a spatial orientation due to the *Johnston organ* – a number of sensory cells on the antennae.

Honey bee evaluates the wind speed and direction by the sensitive long hairs that are located on the head and wings and act as aerodynamic sensors of air-current direction or flight speed relative to air.

The effect of wind on sensor hairs of locust is accompanied with the increasing the frequency of generation of electric pulses from 50-70 Hz to 245 Hz.

A fly has receptors on antennae which are sensitive to wind and help insect to change the position related to the wind direction and speed.

It is necessary to mention that wind plays an important role in formation of soil erosion.

Plant Response to Wind

In addition to the stimulation of nastic movements in plants, the wind is involved in heat and mass transfer, changes the boundary layer resistance, and the rate of evaporation. Wind can also induce significant asymmetry in plant architecture by way of either direct damage (breaking of stems or foliage) or indirect damage via materials such as salt and sand transported by it. A very important agricultural problem is lodging of cereals which can cause a decrease in harvestable yield due to poor light penetration to the canopy, damaged conducting system, and weakening of photosynthetic activity of the plant. Also noteworthy is that wind mediates the deposition and dispersion of soil, plant pollen, seeds, spores, and droplets of agrochemical substances.

References

Henry J.G., Heike G.W. *Environmental Science and Engineering*, Prentice-Hall, Inc., New Jersey, 1996.–778 p.

VIBRATION, EARTHQUAKES AND TSUNAMI

Mechanical Vibration

Vibration refers to mechanical motion, but is accompanied with wasting energy and creating unwanted sound. The main sources of vibration are chain saw, electric shaver, power drill, or electric toothbrush. Besides, vibration has been considered as a feature of the transportation systems – jet planes, vehicles, subway trains etc.

Vibration (from Latin *vibration* – oscillation) is a periodic motion of the particles of an elastic body or medium in alternately opposite directions from the position of equilibrium when that equilibrium has been disturbed.

Mechanical vibration is the term used to describe the continuing periodic motion of a solid body or part of the mass of this body at any frequency. A periodic oscillation in a piece of matter is felt directly by human organism. When the rate of vibration of the solid body ranges between 20 and 20,000 Hz, it may also be referred to as an *acoustic vibration*, which produce the sensation of sound if it is transmitted to a human ear.

The main source of mechanical vibration are chain saw, electric shaver, power drill, electric motors, means of transport such as jet planes, automobile and motor cycle engines, subway trains, construction techniques, industrial units, earthquakes; all of them produce undesirable vibration, sound and noise.

Parameters of Vibration

Displacement is a distance moved by vibrating particle or body from the state of equilibrium at the given moment of time. Distance usually measured in millimeters or micrometers.

Amplitude of vibration is the maximal displacement of a vibrating particle or body from the state of equilibrium.

Phase of vibration is the fraction of a period (the time of one complete vibration) that a particle or a body completes after last passing through the reference, or zero, position.

Frequency of vibration is the number of oscillations the particle or body makes per unit time. The unit of frequency in SI system is hertz (Hz).

Velocity is the rate of change of displacement. The unit of velocity in SI system is m/s.

Acceleration is the rate of change of velocity. The unit of acceleration in SI system is m/s^2.

Jerk the rate of change of acceleration, measured in meters per second cubed.

Vibration can also be measured in dB although this provokes the problems with non-linearity.

Types of Mechanical Waves

The *mechanical wave* is the motion of disturbance of a body or material medium. Let's discuss the main types of mechanical waves.

If the particles of the medium demonstrate the motion in a direction parallel to the direction of wave motion these waves are called *longitudinal* (or *compressional*) *waves*.

A wave in which the particles of the disturbed medium move perpendicular to the direction of wave propagation is called a *transverse wave*.

There are the waves which are neither longitudinal nor transverse, but a combination of both types. The particles of such a wave which is called *surface wave*, are displaced horizontally and vertically from the state of equilibrium; disturbance of the medium has both longitudinal and transverse components.

The Effect of Vibration on Human Organism

The human organism is a rather complex system which consists of a number mobile elements. Each such an element has its own degree of freedom and natural frequency of oscillations. As a whole, human organism demonstrate various levels of sensitivity to external vibration parameters such as intensity, frequency, and duration during the contact with vibrating objects. For example, resonance effect of thorax-abdomen system takes place in the 3-6 Hz range; eyeball respond to resonance frequencies in the region 60 to 90 Hz, while the lower jaw-skull system – between 100 and 200 Hz. However, the fundamental mode of vibration for the skull itself is in the region of 300-400 Hz with resonances for higher modes around 600 to 900 Hz.

There are two types of human vibration:

Hand-Arm Vibration is caused by regular exposure vibrating tools such as screwdrivers, chain saws, nut-runners, grinders, jackhammers, and chippers; these vibrations are transmitted through the hand and arms to the shoulder. The frequency range of hand-arn vibration is 8-100 Hz. The main symptoms are circulation disorder, decreased grip strength and hand sensation, whiteness of parts of the fingers or "white fingers". With continued exposure to vibration, these symptoms may become more severe; the disorder leads to permanent damage or even gangrene.

Whole-Body Vibration is caused by regular exposure to vibrating when worker (tractor driver or forklift truck operator) is sitting, standing or lying on a vibrating surface. These vibration is transmitted to the entire body via the seat or the feet or through standing on vibrating floors. The frequency range of whole-body vibration is 1-80 Hz. Vibration at frequencies below 1 Hz provokes *kinetosis* which is related to the which is related to the disturbance of vestibular apparatus, complex of diseases of cardiovascular, digestive and neuroendocrine systems.

Anti-Vibration Measures

A special attention can be paid to the vibration sensitivity of hands of workers who use the vibrating tools such as pavement breakers, drills, pneumatic chipping hammers and rivetting guns; this sensitivity reaches the highest level in the 8-16 Hz. The precautionary measures include anti-vibration gloves which are using a layer of viscoelastic material; limitation of the time spent by workers on a vibrating surface; mechanical isolation of the vibrating source or surface; installation of vibration damping seats; use of anti-vibration tools.

Measurement of Vibration

A typical vibration measurement system includes a transducer and a recording system which consists of a recorder or frequency analyzer.

Transducer is a device that converts input (mechanical) energy into output (electrical) energy. This device produces an electrical signal which depends on the vibration parameters.

The transducers can be classified according to the principle of operation as follows:

Resistive Transducers use the dependence of the resistance of the conductor on its length. Let's consider the sliding contact which moves along a conductor which is connected with vibrating object. The process of vibration will induce the change of the effective length of conductor and correspondingly of its resistance and current flowing through it. Modern technologies offer the thin-film or printed electric circuits which are operated at the same principle but have small sizes.

Electromagnetic Transducers operate on principle of estimation of *electromagnetic induction* – creation of an electric field in the conductor as a result of the changing magnetic flux; *inductive displacement* by changing the self-inductance of a single coil or mutual inductance between two coils; *capacitance displacement* by fractional changing the capacitance between two electrodes; *Hall effect* – the generation of a voltage across a thin film in a direction perpendicular to the current and the applied magnetic field.

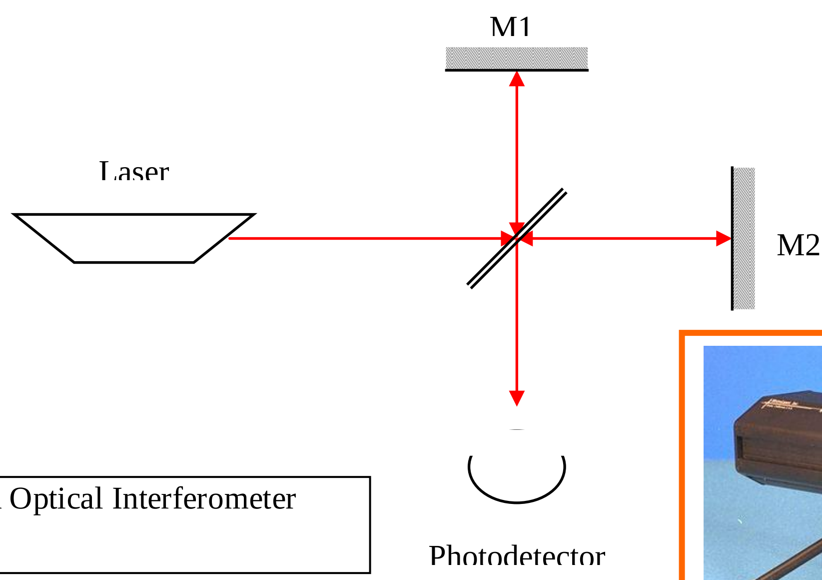
Piezoelectric Transducers contain a piezoelectric element (quartz, barium titanate, lead niobate, turmaline) that produces electrical signals when subjected to mechanical deformation.

The transducers can be classified also according to the parameters of vibration which are measured: we shall consider three of the most common transducers are used in vibration measurements the velocity transducer, accelerometer, and laser vibrometer.

Velocity Transducer (*velocity pickup*) – a transducer whose output is directly proportional to the velocity of the measured unit. It is mounted on the vibrating surface and generates an electric signal which is proportional to the velocity of vibration. This transducer is sensitive and strength, but has large overall size.

Accelerometer generates a signal which is proportional to the acceleration of the vibrating object. It is characterised by high sensitivity, wide frequency range, small weight.

Laser Vibrometer is based on the principle of the detection of the Doppler shift of coherent laser light, that is scattered from a small area of the vibrating object. The object scatters or reflects light from the laser beam and the Doppler frequency shift is used to measure the component of velocity which lies along the axis of the laser beam.
As the laser light has a very high frequency ω (approx. $4.74 \cdot 10^{14}$ Hz), a direct demodulation of the light is not possible. An optical interferometer is therefore used to mix the scattered light coherently with a reference beam. The photo detector measures the intensity of the mixed light whose (beat) frequency is equal to the difference frequency between the reference and the measurement beam.



An Optical Interferometer

Laser Vibrometer
From From www.kenelec.com.au

Vibration and Animals

Stridulation is the production of sound through rubbing together certain body parts. Insects and arthropods demonstrate this ability due to the *stridulatory organs*. Stridulation is known in crickets, grasshoppers, some species of beetles and ants, snakes and spiders.

The vibration and sound are produced due the movement of the *scraper* (lip or ridge) across another ridged surface − the *file*. Such stridulating organisms produce the longitudinal (compressional) waves in the substrate (usually, the plant) as a form of territorial pretensions or for the attraction of a mate. Propagation velocity of such waves is about 500 m/s.

Spiders (*Araneida*) are sensitive to longitudinal vibrations which are produced by trapped insects. These vibration reach each of spider's eight legs. It is necessary to mention that spiders can distinguish the difference between the jerky vibrations of the prey, gentle vibrations that are induced by wind, and specific vibrations of sexual partner. Probably, the spiders can determine the direction of the source of vibrations (prey) through the estimation of either the difference in amplitude of arriving vibrations across each of eight legs or the time difference between signals that reach each leg. The minimal time resolution for spiders is about 2-3 ms.

The mechanoreceptor system of spiders consists of *trichobotria* − thin hairs that occur on the walking legs. These receptors are sensitive to near field particle displacements. The another type of mechanoreceptors is presented by *slit sensilla* which measure displacement in the exoskeleton of the spider. These sensilla form the holes in the cuticle covered by a thin membrane. The loading of the exoskeleton induces the deformation of the covering membrane which leads to nervous activity. The next type of mechanoreceptors involves *lyriform organs* which are able to detect substrate vibrations.

Scorpions (*Scorpionida*) can detect the surface waves that are generated through the sand by insects. The amplitude of vibrations which can be detected by scorpion is about 10^{-9} m. The mechanoreceptor system of scorpion is presented by *basitarsal compound slit sensillum* − thin levers that are found on each leg above the joint and related to the nervous system. These receptors are responsible for reception of the surface waves. In addition, there are *tarsal sensory hairs* that are sensitive to compressional waves. Such a system makes it possible to detect vibrations through the sand around 15 cm with amplitude about 10^{-9} m.

Cockroaches (*Blattodeae*) are also extremely sensitive to surface vibrations: they can detect a movement of about 10^{-9} m − the amplitude of these vibrations is equal to the diameter of hydrogen atom! They are reacting to the air currents and surface vibrations caused by your movement.

Bees (Apis) produce vibrations by thorax muscles during their dancing inside the comb to transfer an information about the feeding. The other bees transmit these vibrations of the substrate through the legs.

Earthquakes

An *earthquake* is a phenomenon that results from and is powered by the sudden release of stored energy that radiates seismic waves. Natural earthquakes can be induced by the mutual movement of tectonic plates which is accompanied with the release of the elastic strain energy and generation of elastic waves.

Earthquakes are characterized by the distribution of the *hypocentres* (the locations inside the Earth where an earthquake originates and which are directly below the *epicentres* – the points on the Earth's surface that is directly above the hypocenters); intensity, duration, mechanisms of origin, and the effects on the Earth's surface.

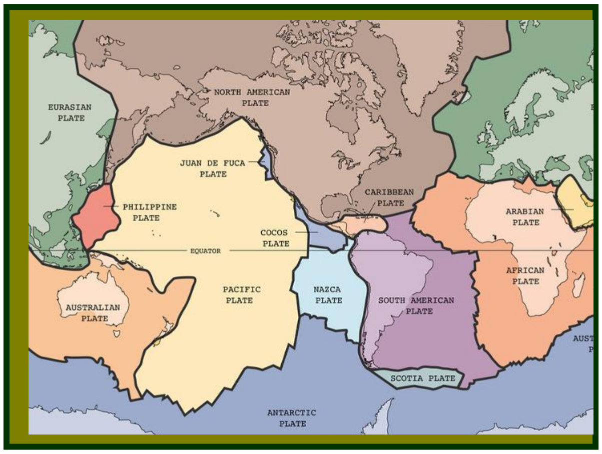


Plate Tectonics Map. From http://earthquake.usgs.gov/learning/topics/?topicID=30&topic=Plate%2520tectonics

Karl Briullov (1799-1852),
“The Last Day of Pompeii”
(1830-33)

Measurement of Earthquakes

Earthquakes can be measured in several ways.

The first way is to measure the magnitude of the earthquake. Magnitude doesn’t depend on the effects to ground structures, but rather on wave amplitude and distance. One such magnitude scale is the *Richter scale*. This magnitude scale is logarithmic.

Magnitude M of earthquake is determined according to the Richter scale as:

$$M = lgA - lgA_0, \qquad (1.9)$$

where A – maximal amplitude of vibrations, that is measured by seismograph; A_0 – function, that corresponds to earthquake amplitude of certain intensity, which is estimated at the certain distance from the hypocentre

The Yasaka Pagoda in Kyoto, Japan, has survived more than five centuries of earthquakes. Photo of the Author.

1.6. Richter scale of earthquake's estimation

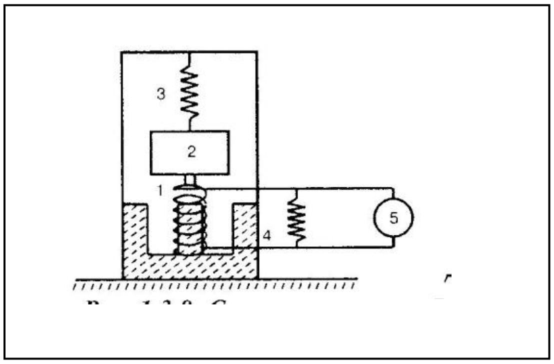
Force	1–2	3	4	5	6	7	8
Energy, J	$4.47 \cdot 10^5$	$7.94 \cdot 10^7$	$2.51 \cdot 10^9$	$7.94 \cdot 10^{10}$	$2.51 \cdot 10^{12}$	$7.94 \cdot 10^{13}$	$2.51 \cdot 10^{15}$

The second way is to describe the earthquake's intensity which is the measure of damage to the surface or the effects on humans. The *modified scale of Mercalli* is used to classify the intensity of an earthquake by examining its effects on the Earth's surface, humans, objects of nature, and man-made structures.

1.7. The modified scale of Mercalli

Force	1	II	III	IV	V	VI
	Instrumental	**Feeble**	**Slight**	**Moderate**	**Rather Strong**	**Strong**
	Not felt except by a very few under especially favorable conditions.	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.	Felt quite noticeably by persons indoors, especially on the upper floors of buildings. Many do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration similar to the passing of a truck. Duration estimated.	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably. Dishes and windows rattle.	Felt by nearly everyone; many awakened. Some dishes and windows broken. Unstable objects overturned. Clocks may stop.	Felt by all; many frightened and run outdoors, walk unsteadily. Windows, dishes, glassware broken; books off shelves; some heavy furniture moved or overturned; a few instances of fallen plaster. Damage slight.
Force	VII	VIII	IX	X	XI	XII
	Very Strong	**Destructive**	**Ruinous**	**Disastrous**	**Very Disastrous**	**Catastrophic**
	Difficult to stand; furniture broken; damage negligible in building of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture moved.	General panic; damage considerable in specially designed structures, well designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.	Some well built wooden structures destroyed; most masonry and frame structures destroyed with foundation. Rails bent.	Few, if any masonry structures remain standing. Bridges destroyed. Rails bent greatly.	Total damage - Almost everything is destroyed. Lines of sight and level distorted. Objects thrown into the air. The ground moves in waves or ripples. Large amounts of rock may move.

The *seismograph* is basically a heavy spring pendulum which is connected with the coil, that is moving in the magnetic field. The motion of the coil induces the electric current that is recorded as *seismogram*. During an earthquake the amplitude of the pendulum's motion is increased.

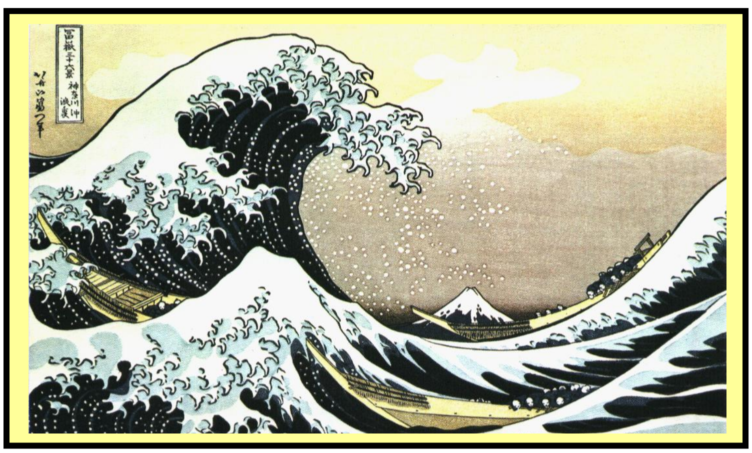


Typical Seismometer: 1 − Coil; 2 − Body; 3 − Spring; 4 − Magnet; 5 − Recording System

Amplification of the Amplitude of Vibration During Earthquake. From www.seed.slb.com

Tsunami

Tsunami (from Japanese *tsu* − harbor, *nami* − wave) is a very large and destructive wave that can be generated as result of vertical movement of the Earth's crust can occur at plate boundaries and undersea earthquakes (volcanic eruption, landslide or meteorite impact can provoke tsunami also). The displaced water mass induces the water waves that propagate across the ocean.



Katsushika Hokusai (1760-1849).
The Great Wave Off Kanagawa(1831)

These waves travel across the ocean at speeds from 500 to 1,000 km/h and have amplitude 60 cm. But when these waves reach the coastline, the amplitude can increase to a height of 30 m or more; the speed of it decreases up to 70 km/h.

Tsunami and Animals

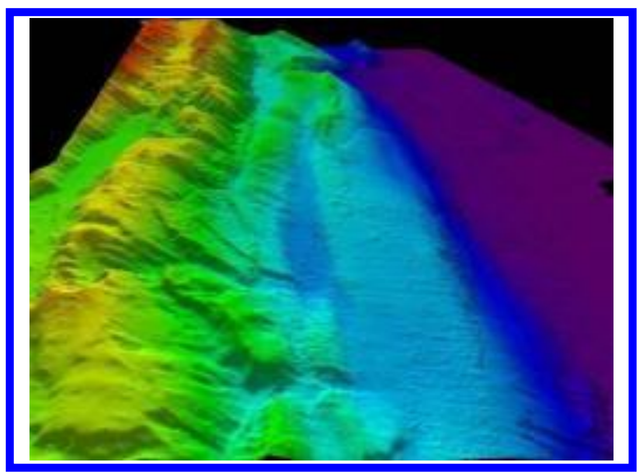
Earthquakes and tsunami, that occurred during last years, killed thousands of people along the ocean coast. But what is interesting – no dead animals was found. There are a number of examples in the literature that animals such as dogs, cats, horses, cows, goats, deer, possums, rats, chickens, fish, reptiles, insects demonstrate unusual behavior before earthquakes. These animals become excited, nervous, aggressive or leave their habitats. Chinese scientists have identified 58 kinds of domestic and wild animals that can be used as predictors of earthquakes.

It is necessary to mention among the possible sensory mechanisms of the earthquake prediction by animals their ability to react to ultrasound or low-frequency electromagnetic radiation emitted by fracturing of crystalline rocks deep in the earth; the earth's magnetic fields that change near epicenters of the earthquakes; variations in electric fields in water; air ionization that induces the changes in the electric field gradient of the atmosphere.

Measurement of Tsunami

The high-resolution multi-beam sonar was used by a UK Royal Navy survey ship to create the image of ocean bed in the area of the Burma plate in the Indian Ocean. The sonic image demonstrates the ridge 1500 meters tall and a massive trench. Such a sonar can be used in the systems of early warning about earthquake and tsunami hazards.

The Sonar Image of the ocean landscape transformed by earthquake (including mountainous ridges 1500 m tall and an ocean trench several km wide) which caused the Asian tsunami.
From
http://www.newscientistspace.com/article/dn6994



Tsunami prevention system is used in the USA at Alaska-Aleutian seismic zone. This system consists of sensitive sensors that are located on the seafloor. When one of such a sensor responds the tsunami wave, it sends acoustic signal to a buoy at the surface; this signal is transferred to radio signal that is launched to the satellite of warning system. You can study the principle of action of such a tsunami monitoring network at the site: http://nctr.pmel.noaa.gov/Mov/DART_04.swf.

Vibrational Processes in Nature. Lotka-Volterra Model.

One of the first models which describes the interactions between two species in an ecosystem, a predator and a prey, was proposed in 1925 by the American biophysicist Alfred Lotka and the Italian mathematician Vito Volterra. The Lotka-Volterra model is based on differential equations.

Differential equation models make it possible to analyze a population at every moment in time. When considering two species, the model will involve two equations, one of which describes how the prey population changes and the second how the predator population changes.

Assuming the prey are rabbits and the predators are foxes, let N_1 and N_2 represent the number of rabbits and foxes, respectively, that are alive at time t. The prey population changes $\left(\frac{dN_1}{dt}\right)$ due to reproduction in proportion to the number (N_1) of rabbits:

$$\frac{dN_1}{dt} = aN_1 \qquad (1.8)$$

where a is a constant.

The prey population decreases the rabbit population at a rate that is proportional to the probability of their meeting (i.e., N_1N_2) which is described by equation:

$$\frac{dN_1}{dt} = -\,bN_1N_2 \qquad (1.9)$$

where b is a constant.

Therefore, changes in the prey population $\left(\frac{dN_1}{dt}\right)$ due to reproduction and predation mediated death can be described by the equation:

$$\frac{dN_1}{dt} = aN_1 - bN_1N_2 \qquad (1.10)$$

The same considerations can be applied to changes in the predator (fox) population due to death during the absence of food (rabbits) N_2 and increases due to finding (meeting) rabbits (N_1N_2):

$$\frac{dN_2}{dt} = -cN_2 + dN_1N_2 \qquad (1.11)$$

where c and d are constants.

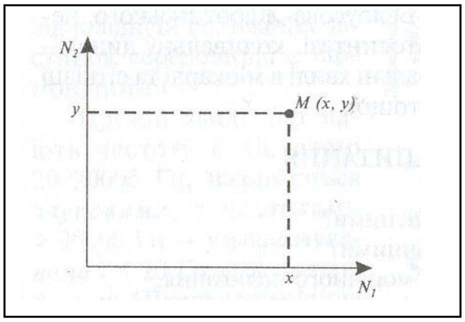
Then the Lotka-Volterra model can be written as:

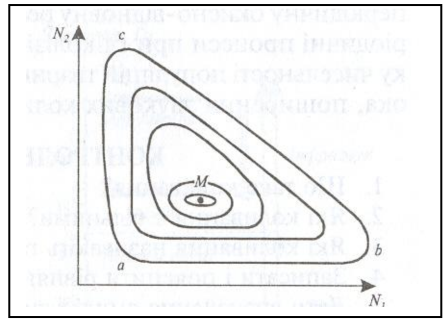
$$\left.\begin{aligned} \frac{dN_1}{dt} &= aN_1 - bN_1N_2 \\ \frac{dN_2}{dt} &= -cN_2 + dN_1N_2 \end{aligned}\right\} \qquad (1.12)$$

A graphical interpretation of the model illustrates that prey and predator populations will be in equilibrium when their rates of change are zero (i.e., births equal deaths). Hence, we can find the equilibrium *isoclines*, the lines where each species is constant, by solving the system of equations (5) when $\frac{dN_1}{dt} = \frac{dN_2}{dt} = 0$. Excluding time ($t$), the following expression is obtained:

$$\frac{dN_1}{dN_2} = \frac{Q(N_1, N_2)}{P(N_1, N_2)}. \qquad (1.13)$$

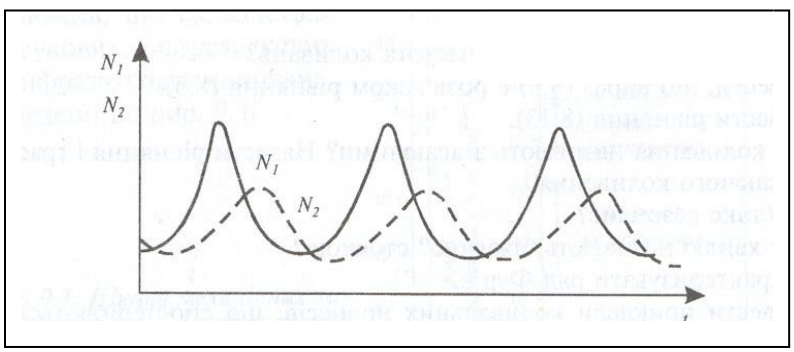
Solution of this equation gives a number of isoclines in predator-prey phase space N_1, N_2 .





It is possible to distinguish the following regions:
a-b – the prey population is growing because of the small population of predators; *b-c* – the predator population is growing while the prey is declining; *c-a* – both are populations declining.

A predator and prey time series plot shows cycles of abundance with the predator cycle lagging behind that of the prey.



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MECHANORECEPTION

General Principles of Sensory Reception

Sensory reception is the ability of living organism to react to the environmental factors.

Sensory system (or *analyser*) is a part of nervous system that transforms the energy of external irritation into activity of nerve cells that induces the appearance and propagation of impulses in the nerve fibre. This system consists of sensory receptors, neural pathways, and parts of brain which are responsible for perception.

Stimulus is the environmental factor that induces sensory sensations of certain quality.

The specialised cells of nervous system that receive information from their environment and transmit it to each other are called *sensory receptors*.

Sensory receptors can be classified according to the stimuli which are detected as mechano–, acousto–, chemo–, thermo–, electro–, magneto–, and photoreceptors.

Mechanoreception

Mechanoreception is the ability of organisms to detect and respond to mechanical stimuli.

Mechanoreceptors can realise: *tactile sensitivity* – detection of pressure, changes of pressure, touch, vibration; *vestibuloreception* – maintenance of equilibrium and orientation in space; *proprioception* – co-ordination of movement of separate parts of the body relative to other neighbouring parts of the body.

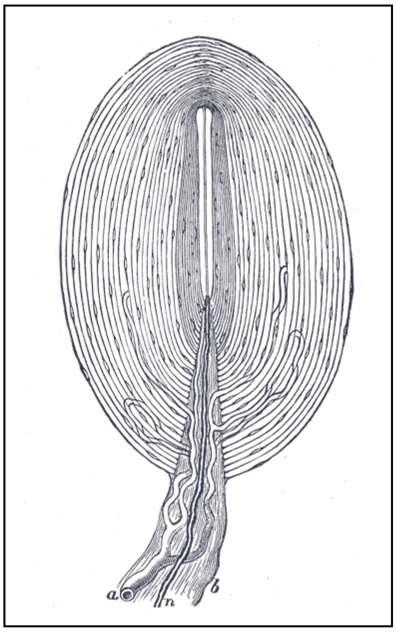
Tactile Sensitivity

There are four main types of the mechanoreceptors of the skin which are capable to realise the tactile sensitivity.

Pacinian corpuscles are located in deep subcutaneous tissue. These corpuscles have ovoid shape of approximately 1 mm in length. Each Pacinian corpuscle consists of 20-60 concentric lamellae separated by gelatinous material. A single afferent nerve ending is located in the centre of corpuscle. All the structure is covered by a layer of connective tissue. The length of these corpuscles is 4-5 μm, the width – 1-2 μm.

Pacinian corpuscles are sensitive to pressure changes and vibrations. The deformation of the corpuscle under mechanical stimulus provides the opening of sodium ions flux through the axon membrane, generation of action potential and generation of a receptor potential.

Fig. .Pacinian corpuscle (http://en.wikipedia.org/wili/Pacinian_corpuscle)



Meissner's corpuscles are found in the skin, particularly in such areas as fingertips, lips, tongue that are sensitive to light touch. These mechanoreceptors consist of flattened supportive cells surrounded by a connective tissue capsule which are related to a single nerve fiber. The length of these receptors is 90-120 μm. External mechanical factor produces the deformation in the corpuscle and generation of an action potential in the nerve.

Merkel disk receptors are distributed in the skin and consist of 30-50 Merkel cells that are connected with an enlarged nerve fiber. This complex of the cells and nerve ending forms tactile corpuscle; a typical size of it is 100-500 μm. These mechanoreceptors are the most sensitive to vibrations at frequencies 5-15 Hz.

Ruffini corpuscles are presented by spindle-shaped receptors which are surrounded by capsule. Diameter of it reaches 150 μm.

Vestibular System

Vestibuloreception is the response to a change in rotary acceleration and deceleration and the direction of displacement in space. Such a response is used by humans and other animals to control their special balance and orientation. The *vestibular system* is located in the inner ear, or *labyrinth*, and consists of three *semicircular canals* located at right angles to each other and a pair of saclike structures called the *utricle* and *saccule*. The utricle is supplied with receptors called *hair cells*. The cells have several hair-like projections into the endolymph and are inserted at its base to a gelatinous mass which contains calcium carbonate crystals called *otoliths*. Semicircular canals which transduce rotational movements and otholiths which transduce linear accelerations.

If the head of an animal is bent at an angle, the semicircular canals alter their orientation, while the endolymph remains at the same place due to inertia. The deflection of the otoliths by gravity results in the transmission of action potentials by the hair cells to the brain at about 100 spikes/second. Interpretation of the bending by the brain occurs through the analysis of changes in the frequency of the action potentials.

Effect of Mechanical Factors on Plants

Many plants exhibit *nastic movements*, which occur in response to external stimuli such as touch, vibration, mechanical injuries, light, and chemical treatment. The direction of nastic movements does not depend on the direction of stimulus. It is necessary to distinguish the very rapid *seismonastic* movements and the *thigmonastic* movements. The first type of movement is caused by touch. For example, when a plant (*Mimosa pudica*) is touched, its leaflets rapidly fold downwards in just seconds. This type of response is used as a way of protection against the wind and insects and other herbivores. Seismonastic movements are related to reversible turgor changes in the *pulvini* - specialized cells at the base of the leaflets.

Thigmonastic movements are related to a response of some plants to mechanical stimulation such as shaking, falling raindrops, mechanical wounding, cutting. For example, *Pisum sativum* and *Passiflora coerulea*, display this type of response to mechanical stimuli.

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GRAVITY

Gravity is the natural force of attraction exerted by an Earth (or other celestial bodies) upon objects at or near its surface, tending to draw them toward the centre of the Earth. Specific characteristics of gravity are: the force of gravity is constant; there are no gradients of gravity; and it is not possible to switch on or off the force of gravity.

Gravity and Unicellular Microorganisms

Gravitaxis of Microorganisms. Light and gravity are the most important external factors which induce vertical migration. Photosynthetic and non-photosynthetic microorganisms can use a light as external stimulus during *photomovement*, which depends on parameters of light, such as direction, intensity, gradients of intensity and wavelength: the moderate levels of illuminance induce the *positive phototaxis* of microorganisms which tend to the water surface to receive solar radiation necessary for viability; the high-level illuminance provokes the *negative phototaxis* of microorganisms which speed to the water depth in order to escape the destructive action of solar radiation. In addition to photomovement many microorganisms show *gravitaxis* – the ability of microorganisms to orient their direction of movement relatively to the gravitational field of the earth. Algae, such as *Euglena gracilis*, *Chlamydomonas nivalis*, *Cryptomonas*, *Peridinium gatunense*, *P. faeroense*, *Amphidinium caterea, Prorocentrum micans, Dunalialla salina,* and protozoa *Paramecium* demonstrate gravitaxis.

Gravitaxis is an opposite to the phototaxis external factor; the microorganisms use the antagonism between these two external factors to search optimal conditions of survival in aquatic medium. That’s why it is difficult to underestimate the importance of gravitaxis as ecological factor.

Mechanisms of Gravitaxis. There are two main hypotheses concerning the possible mechanisms of gravitaxis. According to the first hypothesis there is an uniform distribution of mass in the cell: the rear end of the cell is heavier than the front end; it creates the torque which tends to rotate the cell in vertical position. The cell aligns vertically and its flagellum at the front end makes the cell to move upward. The second hypothesis means the action of a physiological receptor which responds to the direction of gravity and stimulates the transduction chain that triggers the spatial orientation of microorganism through the flagellar beatings.

Gravireception in Microorganisms.The whole cell body which has higher density than the surrounding medium press on the membrane of the endoplasmatic reticulum inside the cell and induces the changes of the electrical potential that stimulates the orientation of the cell towards the gravity.

Gravity and Plants

Gravitropism of Higher Plants. The ability of plants to orient the direction of organ growth relative to the gravitational field of the earth is called *gravitropism.* So, the primary root grows parallel to the vertical toward the centre of the earth (*positive orthogravitropism*); the shoots grow parallel to the vertical away from the center of the earth (*negative orthogravitropism*); stolons, rhizomes, and some lateral branches grow at right angles to the vertical (*diagravitaxis*); secondary and tertiary roots demonstrate the orientation at some intermediate angle between 0^0 and 90^0 (*plagiogravitaxis*). Such spatial distribution of plant organs makes it possible to realize the efficient capture of water and nutrients by the root system and of sunlight − by the shoot system.

Mechanisms of Gravitropism. Higher plants use sedimentation of specific structures such as *statoliths,* which are amyloplasts packed with starch grains within the cell. These grains provide the uniform pressure on the membrane of the endoplasmatic reticulum when the root is oriented vertically; if the root takes the horizontal position this pressure is non-uniform. Accumulation of starch grains which are more dense organelles induces the return of root to its initial position.

Gravity and Animals

Crustaceans, mollusks and other invertabrates have also *statoliths* − special calcium carbonates granules which are sensitive to gravity. These statoliths are located in small cavities that are called *statocysts* lined with sensory hairs. The statolith acts on the certain group of sensory hairs and bends them. When the statocyst changes its position the statolith keeps its spatial position due to inertia and acts on the another group of sensory hairs which send an electrical signal to nervous system.

The response of different species of bee to gravity is realized by *sensilla trichodea* which is located in hair-plates on each side of joint between head and prothorax, thorax and abdomen, coxa and trochanter.

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2. ACOUSTICAL FACTORS OF THE ENVIRONMENT

ACOUSTICS

The branch of science and technology that is devoted to the production, transmission, control, processing, transformation, reception, and interaction with material media of sound, ultrasound, and infrasound waves is called *acoustics*.

Types of Waves

The process of the motion of a disturbance through the medium is called a *wave*. The mechanical disturbances (deformations) in elastic medium are called *elastic* (or *mechanical*) waves.

A *transverse wave* is a travelling wave in which the particles of the disturbed medium move perpendicular to the direction of wave motion.

A *longitudinal wave* is a travelling wave in which the particles of the disturbed medium move parallel to the direction of wave motion.

A *harmonic wave* has a sinusoidal (or cosinusoidal) shape; the relationship between displacement and time can be written in equation form:

$$x = A\sin(\omega t + \varphi_0) \qquad (2.1)$$

where A is a measure of maximum amplitude, ω is a measure of angular frequency, and φ_0 is a measure of the starting phase.

A longitudinal wave that consists of a sequence of pressure pulses or an elastic displacement of the material, whether gas, liquid, or solid, is called an *acoustic wave*.

There are three types of acoustic waves that cover different ranges of frequency – sound, ultrasound, and infrasound waves.

Sound wave is an oscillatory motion of the particles that travels through an elastic medium as a wave. Sound waves lie within the range of sensitivity of the human ear (these waves also are called *audible waves*) and have a frequency ranging between approximately 20 Hz to 20000 Hz.

Ultrasound waves are longitudinal waves with frequencies over 20000 Hz, which is about the upper limit of human hearing.

Infrasonic waves are longitudinal waves with frequencies below the audible range (i.e., less than approximately 20 Hz).

SOUND WAVES

Parameters of Sound

Sound wave is characterized by displacement of the particles from equilibrium, speed of sound, acoustic power, intensity and sound intensity level, and sound pressure.

Particle displacement is a measurement of distance (in metres) of the movement of a particle in a medium as it transmits a wave.

The *speed of sound* describes how much distance such a wave travels in a given amount of time. In dry air, at a temperature of 21 °C the speed of sound is 344 m/s.

Acoustic power (or *sound power*) P_{ac} is a measure of sonic energy E per time t unit.

The *intensity* of the sound wave is the amount of energy that is transported through a given area of the medium per unit of time (or as the sound power P_{ac} per unit area). The intensity of a sound wave is measured in Watts/meter^2. The intensity of the faintest sound which can just be heard is about 10^{-12} W/m^2; the loudest tolerable sound has an intensity of approximately 1 W/m^2.

Sound pressure is the pressure deviation from the local ambient pressure caused by a sound wave.

Sound intensity level or *acoustic intensity level* is a logarithmic measure of the sound intensity in comparison to the reference level of 0 dB.

The measure of a ratio of two sound intensities is

$$L_J = 10\lg(J_1/J_0) \text{ dB}, \qquad (2.2)$$

where J_1 and J_0 are the intensities. The sound intensity level is measured in decibels (dB). dB is dimensionless. Here $J_0 = 10^{-12}$ W/m^2 is the standard reference sound intensity (which corresponds to the threshold of human hearing).

Table 2.1 gives some typical values for the sound levels from various sources or causing specific symptoms in humans.

2.1. Typical values of the sound levels from various sources or causing specific symptoms.

Source of Sound	**Sound Level, dB**
Damage of eardrum	160
Nearby jet airplane	150
Threshold of pain	130
Rock concert	120
Subway	100
Busy traffic	80
Vacuum cleaner	70
Normal conversation	50
Mosquito buzzling	40
Rustling leaves	10

According to the New York Post Maria Sharapova shouts at 101.2 decibels. For comparison, the sound level of rock concert is 110 decibels.

The principal peculiarities of sound wave are the following:

1. Sound waves propagate through the medium, induce the vibration of particles of the medium and correspondingly the changes of density and pressure; these waves cannot travel in vacuum.
2. Sound waves transfer mechanical energy.
3. Sound waves are longitudinal waves because the particles of the disturbed medium move in a direction parallel to the direction of wave movement;
4. The speed of sound waves increase on travelling from gases (330 m/s in air) to liquids (1493 m/s in water) and solids (5100 m/s in aluminium).

Physical Characteristics of Sound Waves

Sound has three physical quantities: *frequency* (Ω), *intensity* (I), and *waveform* which correspond to the characteristics of sound that we hear – *pitch*, *loudness*, and *tone quality*.

The *pitch* is the term that is used for a stimulus parameter (i.e., synonymous to frequency) and for an attribute of auditory sensation: pitch is that auditory attribute of sound according to which sounds can be ordered on a scale from low to high.

The *waveform* is the pictorial representation of the form or shape of a wave, obtained by plotting the amplitude of the wave with respect to time (square, sine, or triangular waves).

Loudness is the perceptual intensity of sound. Loudness depends importantly on the physical intensity of sound, and loudness also depends on other physical properties of sound, such as frequency and duration. Sound waves with frequencies between 1000 and 5000 Hz are louder than sound waves that have the same intensity but lower or higher frequencies

Tone quality (or *timbre*) describes those characteristics of sound which allow the ear to distinguish sounds which have the same pitch and loudness; timbre is mainly determined by the harmonic content of a sound.

Sound Production

Mammals. The mechanism of sound production is related to the vibrations of elastic cords or folds of the *larynx*. These vibrations are created during the passage of air from the lungs through the larynx. The modulation and individualization of the produced sounds are realized due to the participation of tongue or teeth. In addition, the resonance cavity such as bony sinuses and air sacs in the pharynx make a contribution to sound production.

Birds. The vocal organ of the birds is presented by a *syrinx* − a bony structure at the base of the trachea. The sound is produced by the flow of air which is passing through this small orifice and by corresponding vibrations of the *Membrana tympaniformis* (the walls of the syrinx). The sound modulation is realized due to the changes of the membrane tension and the bronchial opening.

Insects. The production of sound by insects (e.g., *Lepidoptera*, *Coleoptera* and *Hymenoptera*) is accompanied with the *stridulation* − wing movement, striking or rubbing certain appendages against other parts of their bodies.

Male *Cicada* uses the paired *timbals* − special membranes in the abdomen which are responsible for the sound production. The enlarged cavities derived from trachea play role of sound resonators which amplify rapid vibrations of these membranes. The sound loudness of some cicada (*Brevisana brevis*) reaches 106 dB at distance 0.5 m. The modulation of sound is realized by wiggling the abdomens toward and away from the tree where cicada is visiting.

Annual cicada, *Tibicen linnei*
http://en.wikipedia.org/wiki/Cicada

*Fish***.** Sounds are produced by fish due to the *drumming* (contracting and expanding of the swim bladder with the sonic muscle) which causes the water vibrations, or by *stridulation* between bony parts (teeth or fin spines) of the body, or through *hydrodynamic sound* − quick changes of the swimming speed and direction. The frequency range of these sounds is 40-2500 Hz for drumming; 20-12000 Hz for stridulation; 20-5000 for hydrodynamic sounds.

Aquatic animals. Cetaceans produce sounds with a pair of *phonic lips* which are located in the nasal system (the *Odontoceti* − toothed whales, including dolphins). Dolphins produce clicks and whistles. Some whales (the *Mysticeti* − baleen whales including blue whale) do not have phonic lip structure; probably they recycle air around the body to produce sound. Baleen whale produces low-frequency sounds for long-distant communication and navigation. In addition, the cetaceans produce sound by slapping the sea surface with their flippers and tail.

Pinnipeds can produce barking, crying, growling, roaring, and snorting which are generated by the vocal cords. Elephant seals, for example, produce a wide range of grunts, roars, and belches. Some pinnipeds can produce higher frequency sounds including bell-like ringing, clicks, rains of pulses, whistles, and warblers; these sounds are produced by organs other than vocal cords.

Sound Propagation

There are several types of physical processes which accompany the sound propagation in nature.

The *attenuation of sound* means the decrease of sound pressure with the distance from the source of sound due to geometric spreading. This attenuation can reach 6-12 dB (two times) decrease in sound pressure per doubling of the distance depending on the size of sound source. The geometric spreading loss depends on the propagation geometry but not on the medium.

The *reflection of sound* occurs when the dimensions of the surface roughness is below a wavelength. This process can be realized during interaction of sound with air-soil, air-water interfaces and with the interfaces of air volumes with different temperatures or humidities.

The level of reflection depends also on the distance of sound propagation from the ground and on the frequency of sound wave − ultrasound waves propagate parallel to the ground without influence of the surface roughness.

The *absorption of sound* is related to the dissipation of sound energy into the heat or other forms of energy. This process depends strongly on the frequency of sound − attenuation of sound increases from 10^{-2} to 10^{2} dB/100 m in air and from 10^{-4} to 1 dB/100 m in sea water during increasing sound frequency from 100 Hz to 100 kHz.

The *refraction of sound* is caused by gradients of temperature or density of the medium. For example, the velocity of sound increases about 0.6 m/s for each increase of 1 ^{0}C of the air temperature.

The *diffraction* or *scattering* takes place when the size of the object is of the same magnitude as wavelength of sound wave.

The propagation of sound in water medium has some peculiarities. Sound absorption is much higher in air than underwater. That’s why the region of acoustic communication of aquatic animals is considerably larger than for terrestrial animals.

As soon as the sound velocity, density and acoustic impedance of water are higher than of corresponding air parameters, there is a significant difference in sound propagation in air and underwater. The air-water interface play role of specific sound reflector which determines propagation of sound waves and their interaction with sourroundings.

At least, the water medium is characterised by the variations in pressure with depth which increases at a rate of one atmosphere for each 10 m of the depth. That’s why there is a considerable effect of water pressure on the process of sound propagation.

Sound Communication

Animal Communication is an interaction between animals in which information transmitted from one animal or group of animals affects the behaviour of other animals.

Anatomical structure of vocal organs determines the main characteristics of sound signals which are produced by animals − intensity, frequency, spectral composition and range, duration.

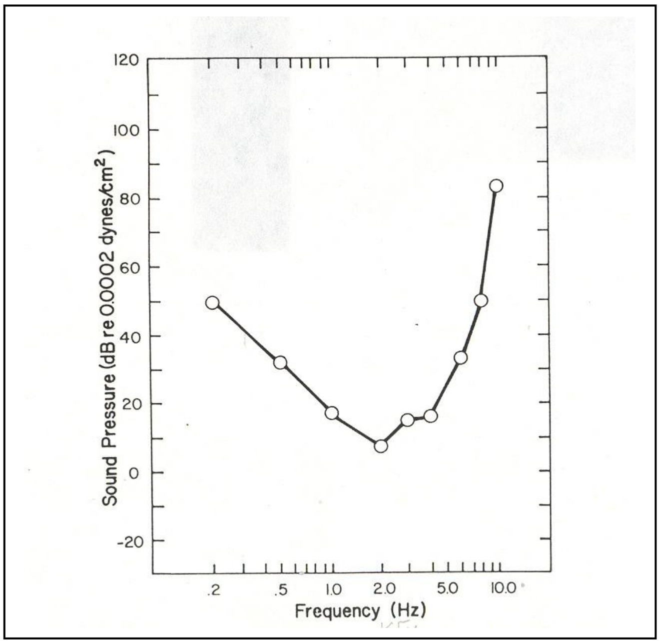
Terrestrial and marine animals including mammals, birds, fish, amphibians, and reptiles, produce sounds within human frequency range (20 − 20 000 Hz) while some animals demonstrate the ability to produce acoustic signals in ultrasound or infrasound frequency range (Table 2.2).

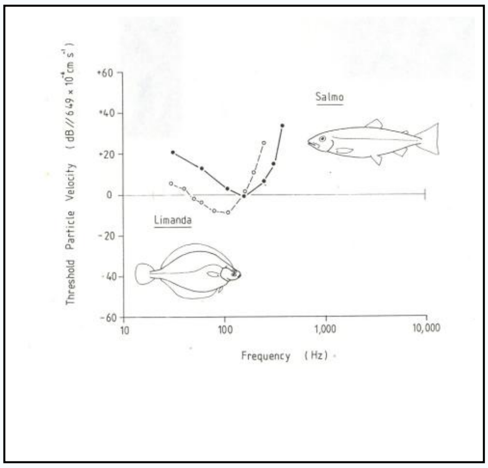
2.2. Frequency range and maximum sensitivity of living organisms

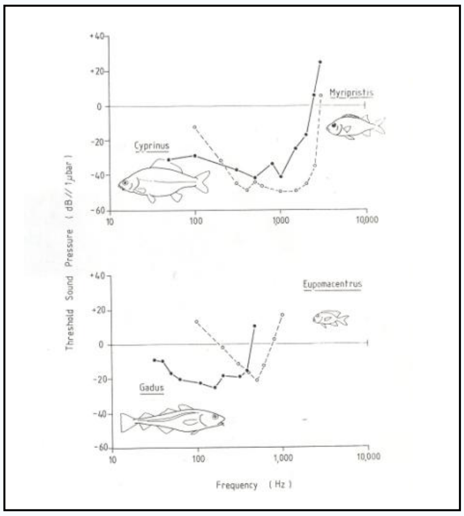
Terrestrial Animals	**Frequency range**	**Maximum Sensitivity**
Cow *Bos Taurus*	23 Hz − 35 kHz	
Horse *Equus caballus*	55 Hz −33,5kHz	2 kHz
Sheep *Ovis aries*	100 Hz − 30 kHz	10 kHz
Marine Animals	**Frequency range**	**Maximum Sensitivity**
Bottlenose dolphin	250 Hz − 150 kHz	
Harbor porpoises	40 Hz − 150 kHz	
Toothed whale	40 Hz − 325 kHz	
Baleen whales	below 5,000 Hz	
Orca	100 Hz − 40 kHz	
Birds	**Frequency range**	**Maximum Sensitivity**
Canary	250 Hz − 8 kHz	
Owl	200 Hz − 12 kHz	2 kHz
Chicken	125 Hz − 2 kHz	
Fish		**Maximum Sensitivity**
Cod *Gadus morhua*	2 − 500 Hz,	20 Hz
Goldfish *Carassius auratus*	5 −2,000 Hz	400 Hz
Goliath grouper and Black drum	45 − 60 Hz	1000 Hz
Toadfish spp. and Silver perch	250 − 300 Hz	1000 Hz

The ability of animal to perceive different sound frequencies is characterized by an *audiogram* − graphical dependence of sensitivity threshold on the sound frequency.

Generalized avian auditory threshold function. After Dooling, 1980.







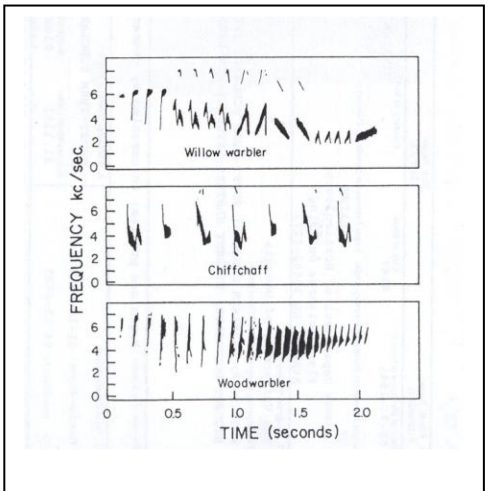
Audiograms for two “non-specialist” species of teleost fish, the dab *Limanda limanda* (Chapman and Sand, 1974) and the salmon *Salmo salar* (Hawkins and Johnstone, 1976). These two species are sensitive to particle motion.

Audiograms of fish – hearing “specialists”: the carp *Cyprinus carpio* and the soldier fish *Myripristis kuntee* have an intimate connection between the swimbladder and the ear; the damsel fish *Eupomacentrus partitus* and the cod *Gadus morhua* have the swimbladder that is not directly connected by the ear (Coombs and Popper, 1979).

Acoustic communication between animals makes it possible to perform important vital functions such as searching and gathering food, educating and protecting young generation, reserving territory, identifying and attracting mates, warning against the predators, frightening competitors and navigating.

The sounds of animals can be used for intraspecific (between animals of the same species) or interspecific (between different animal species) communication.

The birds demonstrate an especially rich assortment of acoustic signals − *bird songs* which are continuous and melodious for human ear, and *bird calls* which are short sounds. Dependence of the intensity and frequency of acoustic signals of the birds on the time is called *sonogram*.

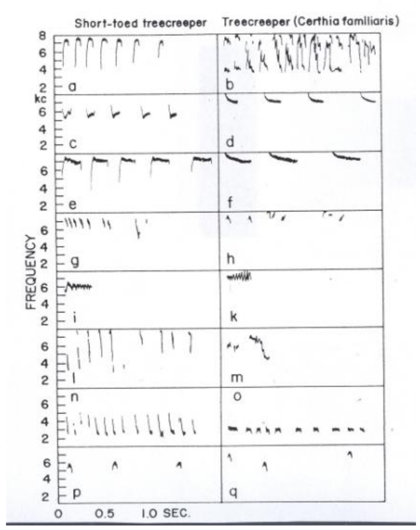


Sonographs of song for three species of warbler (after Marbler, 1960)

Hume’s Leaf Warbler *Phylloscopus humei* http://en.wikipedia.org/wiki/Image:Hume%27s_Warbler_I2_IMG_3401.jpg

The sonograms of possible variations of sound that are produced by the representatives of two species of treecreeper are characterised by the variants: *a−d* are the signals which are used for territory designating; *e−f* are the signals of alarm; *g−k* correspond to the contact with relatives; *l−m* are used for common sleeping during cold weather; *a−o* are intended for feeding of young birds; *p−q* are calling the nestlings to sleep.

The sonograms of bird song for three species of warbler are different and can be used as taxonomic criteria.



Bird Sonograms. From G. A. Thielcke, " *Bird Sounds*", 1976

Sort Toed Treecreeper. From *andaluciaguides.com*

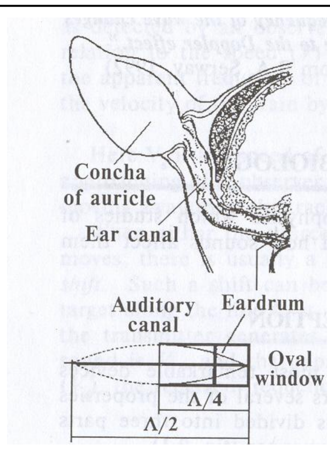
On the whole, animals, birds and fish use the variations in bandwidths, sound frequencies, modulation, long elements and inter-element intervals between sounds during acoustic communication.

ACOUSTORECEPTION

Mammals. The *ear* is consists of three parts designated as *outer*, *middle* and *inner* ear.

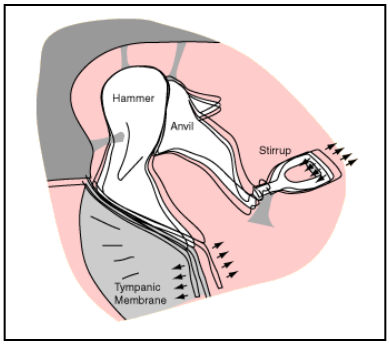
In *outer ear* the sound is directed from *concha of auricle* through *ear canal* to the extremely elastic membrane − *eardrum.* The function of outer ear is *optimization and preliminary amplification of the important sound frequencies*. This function is realized due to such a phenomenon as *resonance.* Resonance arises from the production of standing waves along the auditory canal and the middle ear. The fundamental resonant frequency occurs when the length of the canal is equal to one-quarter of the corresponding acoustic wavelength.

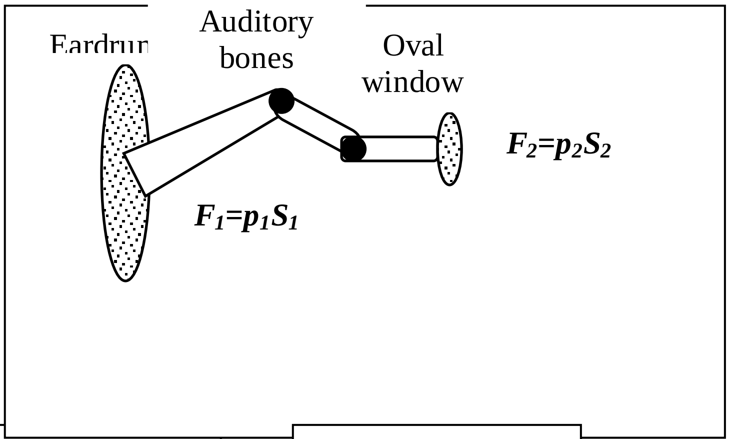
Structure of outer ear and formation of standing wave in the outer ear



The *middle ear* has two functions – *transduction and amplification.* Here ear drum transmits the sound vibrations on an *auditory bones* (or *auditory ossicles*) such as the *malleus*, *incus*, and *stapes*. The main function of these small bones is to convert the sound energy into mechanical energy. This conversion is realized due to two principal mechanisms. The first one is the *lever action* of auditory bones; the lever which is created by the ossicles provides a factor of about 1.4 in force advantage. The second mechanism is associated with *pressure amplification* due to different areas of eardrum (55 mm^2) and oval window (3.2 mm^2).

Let's express the force as a product of the pressure on the eardrum and the area of eardrum: $(F_1) = p_e 55$. The force advantage of the lever system, which is created by the ossicles, is about 1.4. This means that the force (F_{ow}) on the oval window is 1.4 times F_1, or $F_{ow} = 1.4 F_1$. Then we can express p_1 in terms of F_{ow} as $p_e = F_1/55 = F_{ow}/(1.4)(55) = F_{ow}/77$. The area of the oval window is about 3.2 mm^2, so the pressure on the oval window is given by $p_{ow} = F_{ow}/3.2$. The theoretical pressure amplification $p_{ow}/ p_e = (F_{ow}/3.2)/(F_{ow}/77) = 24$. The results of the experimental estimation of pressure amplification have been reported to be about 17.

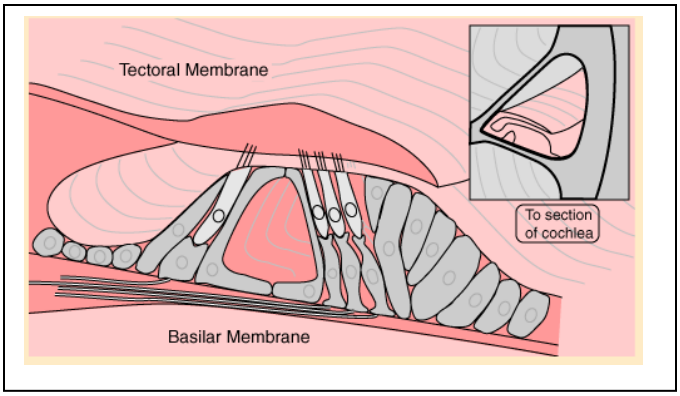




Ossicle Vibration. From: http://hyperphysics.phy-astr.gsu.edu/hbase/sound/oss.html

Model of middle ear

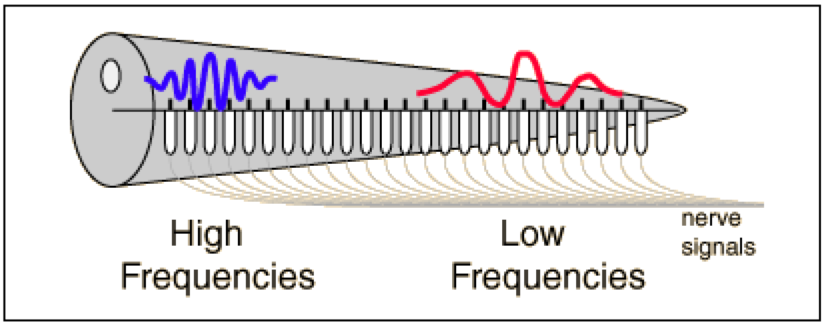
The functions of the inner ear are *pitch resolution and detection.* The inner ear is located in the *cochlea.* Essentially the organ contains two fluid-filled chambers divided by a



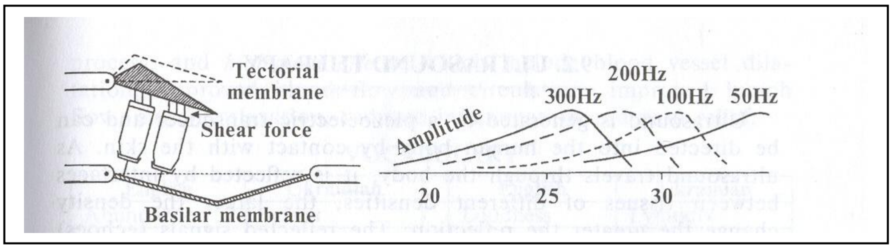
Inner Ear. From hyperphysics.phy-astr.gsu.edu/hbase/sound/corti.html

membrane, called the *basilar membrane.* The basilar membrane contains about 16,000-20,000 *hair cells,* which are arranged along the length of basilar membrane. These hairs cells are located on the basilar membrane with the *tectorial membrane* directly over them; they are excited by shear force occurring from the side of tectorial membrane which moves in response to pressure variations in the fluid space of inner ear. These movements stimulate the deformation of certain groups of hair cells: high sound frequencies induce the deformation of the cells

near oval window, while low sound frequencies travel along the membrane and excite the hair cells which are located at the remote regions of the membrane.
The nervous system transmits the signal from the hair cells to the brain. According to the *place theory* (*hypothesis of Bekesy*), different frequencies will cause a maximum vibration amplitude at different points along membrane.



Place Theory (Hypothesis of Bekesy). From hyperphysics.phy-astr.gsu.edu/hbase/sound/corti.html



Birds. Birds have not the externally visible part of the ear; the outer ear consists of the outer opening of the ear canal which leads to a recessed ear drum; this ear opening is surrounded by specialized feathers in the form of a funnel which act as an efficient sound collector. The middle ear has a single bone stretched across it called the *columella*. This ear has, like in mammals, three auditory bones. The inner ear consists of five parts, of which two, the semicircular canals and the utricle are concerned with vestibuloreception. The other three are the *cochlea*, the *lagena* and the *sacculus*. The lagena makes it possible to detect low frequency sounds, while the sacculus can detect high frequency sounds; the cochlea contains special sensory hairs which convert the sound vibrations into electrical impulses to be sent into the brain.

There are specific features of the birds' auditory system. Some birds (e.g. owls) possess *binocular hearing* due to asymmetrical arrangement of ears (one ear is lower on the skull than the other) that means sounds from a single source reach the ears at slightly different times. The barn owl, *Tyto alba*, for instance, is capable of orienting to a sound source in complete darkness with an error of less than 2 degrees.

One of the most remarkable feature of the birds' auditory system is the ability to resolve the *frequency modulation* − small (10-15 Hz) differences that exist in the frequency of most sounds.

Aquatic Mammals. The principal feature of auditory system of cetaceans is the absence of external ears. The ears of cetacenous are barely noticeable, being marked only by a small hole just behind the eye. Baleen whales have well developed hearing in the low frequency ranges but they lack the ability to hear high frequency sounds. They react to underwater noises such as boat engines. It is known that baleen whales have a small external ear opening on each side of the head. Each opening leads to a narrow auditory canal that is completely closed by a waxy substance, which is thought to transmit underwater sounds to the inner ear.

The middle and inner ear follow the basic mammalian ear structure. The exact mechanism for sound reception in baleen whales is unknown. The foam which surrounds the ear bones, provides the isolation of sound waves traveling through water and living tissues; such a foam enables a whale to orient to sound direction.

Dolphins do have small external ear openings (2-3 mm in diameter) behind the eye. Each opening leads to a reduced ear canal and an eardrum. Acoustoreception is carried out due to the bone conduction (lower jaw) and tissue conduction (soft tissue and bone surrounding the ear). Sounds are received and conducted through the lower jaw to the middle ear, inner ear, and then to hearing centers in the brain via the auditory nerve.

Fish. Auditory system consists of a labyrinth, or inner ear which extends fish hearing to higher frequencies. Sound waves travel to chambers where small granules called *otholits* are located above the macular membrane densely covered with more than 100,000 sensory hair cells. Incident sound oscillates the otolith which has greater inertia than its surroundings. The otholits deform the membrane, stimulate hair cells and induce action potentials in the neurons of the auditory nerve.

The gas bladders of some fish also provide an area of variable density. Vibrations pass through the gas bladder and travel through a pathway of small bones called *Weber ossicles.* These serve to connect the gas bladder directly with the inner ear of the fish.

NOISE

There are several definitions of *noise*. The first one determines noise as sound waves with unexpected and aperiodic change of intensity and frequency; according the second definition noise is a sound which superimposes on the other sound and produces undesired sound after interaction; the third definition of noise means each sound that is unwanted and unpleasant for human.

Environmental noise is the collection of offending sounds to which humans are involuntarily exposed.

Noise pollution is displeasing human or machine created sound that disrupts the environment.

Intensity Distribution of Noise

The range of sound intensity which surrounds us is very large. Minimal intensity of noise (for example, whispering or rustling leaves) is about 10^{-12} W/m^2, while maximal value (such as jet airplane taking off or jackhammer) reaches 10 W/m^2. The most common noise sources can be divided into aerodynamic systems (fans, ventilators), machinery (compressors, electric motors, woodworking machines, pneumatic tools), transport means (trains, cars, aircrafts), domestic devices (audio systems, musical instruments).

The recommended levels of noise are: in National Parks – 30-35 dB; in hospitals, apartments, buildings – 34-37 dB; in supermarkets, factories – 56-66 dB.

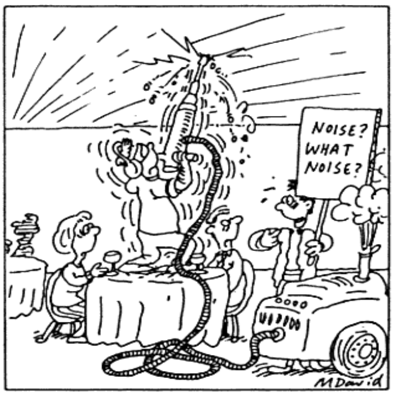
The noise intensity level of nearby jet airplane reaches 150 dB. From www.panorthfield.co.uk

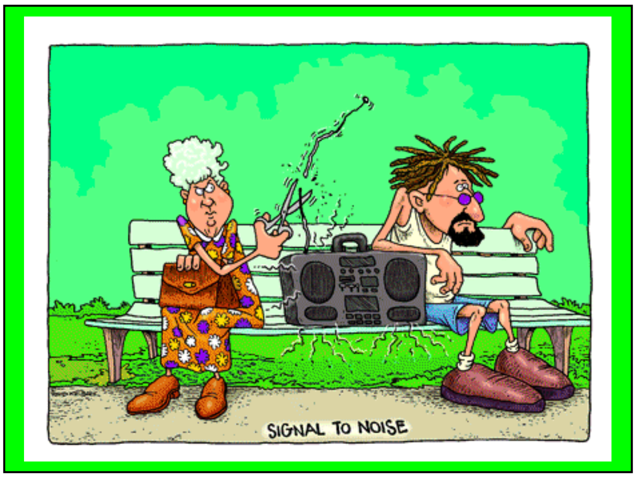
Noise Health Effects

The damage done by noise depends on the loudness and the time of exposure. Noise that reaches the inner ear can provoke the temporary hearing loss. After certain period of time hearing may be restored. This is *temporary* hearing loss. Under long-term exposure to intense noise or short-term exposure to very intense noises the hearing loss will become *permanent*.

The elevated sound levels cause trauma to the cochlear structure in the inner ear. This hearing loss results from the destruction of the inner ear-cells which can never be replaced or repaired.

High intensity noise induces cardiovascular effects, rise in blood pressure, increased incidence of coronary artery disease.





http://mdavid.com.au/cartoons/cartoon25.html

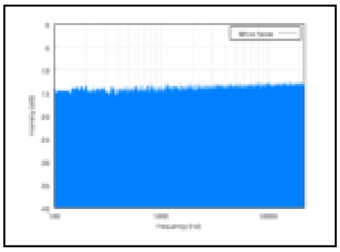
Hearing loss can be evaluated by *noise-induced temporary threshold shift* (*NITTS*), which is determined through the measurement of hearing sensitivity before and after noise exposure. This shift can be temporary or permanent depending on the intensity, frequency and duration of the noise.

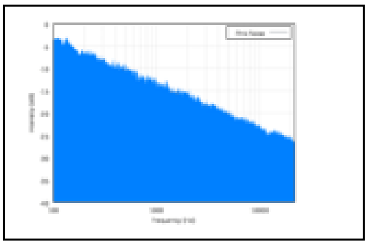
Noise pollution can be also harmful to animals through the disturbance of their natural cycles. The feeding behaviour, breeding rituals, migration paths can be changed by noise. The most sensational damage caused by noise pollution is the death of certain species of beaked whales provoked by extremely loud (about 200 dB) sound of military sonar.

Frequency Distribution of Noise

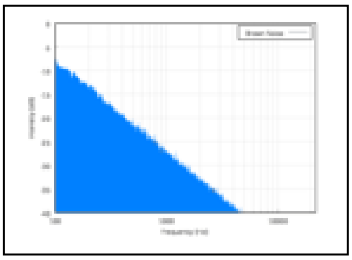
The forms of noise with various frequency characteristics can be classified by "colour"; this term is derived from an analogy with spectrum of light wave frequencies.

White noise is a signal with a flat frequency spectrum in linear space.

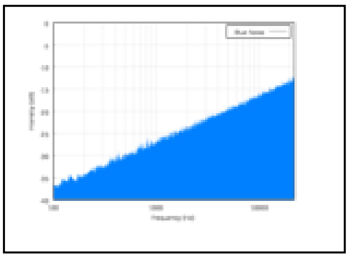




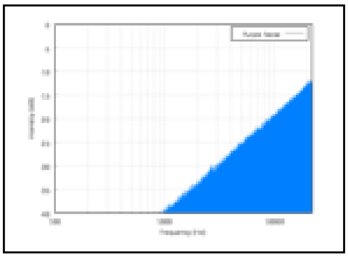
Pink noise is characterised with a flat frequency spectrum in logarithmic space.



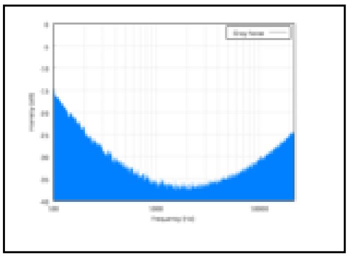
Brown (red) noise



Blue noise



Purple noise



Grey Noise

Measurement of Noise

The following devices are used for monitoring of airport or industrial noise:

Capacitor microphone consists of the diaphragm, that acts as one plate of a capacitor, and vibrations produce changes in the distance between the plates. The charge Q of the plates, voltage U maintained across the capacitor, and capacitance C are related to the following expression:

$$Q = CU, \qquad (2.3)$$

where the capacitance of the plates is inversely proportional to the distance between them.

Inside the Oktava 319 condenser microphone. From http.//en/wikipedia.org/wiki/ Microphone

Measurement of Environmental Noise

A piezo microphone uses the effect of piezoelectricity – the ability of some materials to produce a voltage when subjected to pressure and to convert vibrations into an electrical signal. Such a microphone are often used to record sounds in unusual environment (underwater, for instance).

An electret microphone is based on the electret effect – the ability of dielectric materials to be polarized. The name comes from *electr*ostatic and magn*et*; a static charge is embedded in an electret by alignment of the static chasrges in the material, similar the way a magnet is made by aligning the magnetic domains in a piece of iron. These microphones are low-cost, have the long-term stability, but low quality.

Noise Analysers can be used to determine the possibility of controls for individual noise sources and to evaluate hearing protectors. These devices consist of octave-band filters with the following centre frequencies: 31.5; 63; 125; 250; 500; 1,000; 2,000; 4,000; 8,000; and 16,000 Hz. A sound level meter measures the sound power at each of these frequencies.

Sound Insulation

The direct transmission of sound between two rooms is determined by the insulation properties of the separation wall. If I_0 is the intensity that is hitting the wall, t is coefficient of transmission of the wall material, I_t is a part of sound that is transmitted, the *air insulation* can be defined as:

$$R = 10\lg\frac{I_0}{I_t}. \qquad (2.4)$$

ANIMALS AND ULTRASOUND

Ultrasound Communication and Echolocation

The primary unique features of ultrasound are its *high energy* and *rectilinearity of propagation*. These properties of ultrasound open the wide horizons in animal world.

Acoustic communication of animals means the reception and use of ultrasound signals by animals during interaction between them.

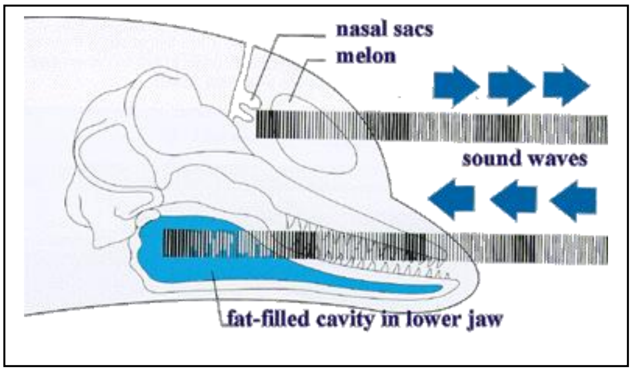
The animals produce and use ultrasound signals for *echolocation* − emission of sound waves and receiving the echo in order to obtain information about size, location, and movement of the objects or to navigate. In addition, the animals, and some insects especially use ultrasound for social communication.

Bats (*Vespertiloidei*) use ultrasonic signals to detect insect prey, to locate fruits and trees, or for navigation. Some of the bats (*Megachiroptera*) produce short clicks, while the others (*Microchiroptera*) generate frequency-modulated or constant frequency pulses. The frequency range of ultrasound signals which are produced by bats is 14,000 – 100,000 Hz. The frequency of pulses may vary from 4-10 to150-200 pulses per second.

Dogs can hear ultrasound at a frequency 18-22 kHz. This ability makes it possible to avoid an approaching vampire bats. The special dog whistles which produce the ultrasound signals are used by dogs owners. The upper limit of hearing of *cats* (50 kHz) and *rats* makes it possible to detect the high-frequency cries of their prey and to catch them.

Toothed whales such as dolphins, porpoises, orcas and sperm whales use ultrasound signals for detection of underwater objects and communication. The frequency of the ultrasound signals produced by dolphins ranges from 0.25 to 150 kHz. The lower frequency ultrasound (from 0.25 to 50 kHz) are used in social communication. Higher frequency signals (from 40 to 150 kHz) probably are used in echolocation. Each dolphin produce exceptionally individual frequency-varying ultrasound whistles.

Echolocation is realized in such a way: dolphin produces the directional pulses (clicks) 50-128 microseconds by duration by passing air through the phonic lips. These signals are reflected from concave bone in cranium and are focused by it. Then these pulses pass through the *melon* − a large fatty organ that consists of lipids of differing densities and plays a role of specific acoustic lens to focus ultrasound waves into a beam which is directed in front of the animal.



Echolocation system of dolphin. From www.dolphins-and-more.com

The ultrasound waves propagates at a speed of about 1.5 km/s; after reflection from the underwater object these waves return as echo to the dolphin. Ultrasound reception occurs in the fat-filled cavities of the lower jaw bones from which the ultrasound signals are transmitted through the middle and inner ear to the brain. Such echolocation system can determine direction, location, size, shape and velocity of movement of underwater objects.

Fish. Several types of fish (the order *Clupeiformes*, members of the subfamily *Alosinae*), can detect ultrasounds up to 180 kHz; the other subfamilies (e.g. herrings *Clupeidae*) can hear only up to 4 kHz.

Moth. The ultrasound irradiation of moth by bats causes flying moth to make sharp maneuvres to escape the predator attack. In addition the ultrasound signals (up to 80 kHz) which are produced by the wings are used by moth (three species of the family *Pyralidae*: *Ephestia cautella* (Walker), *Ephestia kuehniella* Zeller, *Plodia interpunctella* (Hübner)) in mating behaviour.

Ants. These insects (the genus *Ectatomma*)produce the ultrasound signals (chirps) by alternative movement of parts of body (a simple plectrum against a pars stridens). These signals has frequency up to 75 kHz .

INFRASOUND WAVES AND ANIMALS

Infrasound waves are characterized with high intensity, ability to propagate along the ground surface at long distances without serious dissipation.

Sources of infrasound in nature include plants and trees, earthquakes and tsunami, hurricanes, tornado and storms, eruption of volcanoes, avalanches, thunderstorms, floods and waterfalls. Industrial society offers such sources of infrasound waves as cars, aircrafts, motorcycles, air heating and cooling systems, agricultural mechanisms. Heart beatings, lung oscillations, activity of bowel, vibration of vocal system are accompanied with the generation of infrasound.

Human organism is sensitive to infrasound − people feel the state of fear, anxiety, uneasiness, extreme sorrow, nausea, imbalance and spatial disorientation.

Animals such as elephants, rhinoceros, hippopotamus, giraffes, tigers, okapi, alligators, mole rats, some birds and fish use infrasound for detection of prey, communication and navigation.

So, Asian elephants (*Elephas maximus*) produce infrasound signals ranged in frequency 14-24 Hz with intensity level 70-100 dB while African elephants (*Loxodonta Africana*) produce the infrasound signals in the range of 14-35 Hz with the intensity level up to 90 Db.

These signals let them communicate over several miles. Such infrasound communication makes it possible to detect danger from poachers and warn others, find the sources of water, inform about the state of estrus in females and to attract male elephants, gather all the members of family, especially juveniles, together over vast areas.

Infrasound is produced by elephant due to the flutter and vibration of the skin during blowing air through nasal passage. Large outer ear of the elephant provides optimal reception of infrasound signals: the objects smaller than the acoustic wavelength are poor receiving satructures for these waves. Low frequencies of infrasound correspond to long wavelengths which are only reflected from very large objects and can be used for communication in forest, scrub and grassland environment.

Elephants. From www.travelwithachallenge.com

The giraffe (*Giraffe camelonardalis reticulate*) demonstrates the ability to generate infrasound measured from 14 Hz (60 dB) tj 250-275 Hz (30 dB) with dominant frequencies between 20-40 Yz.

Whales (*Cetacea*) use infrasound for the purpose of mating; these infrasound waves propagates through water at long (3,000 mile for fin whale) distance. In addition, whales use focused infrasound to paralyze large squids and fish during hunting.

Tigers (*Panthera tigris*) are able to produce and hear infrasound with frequency about 18-20 Hz that let them communicate through dense forest and bushes. There is opinion that infrasound components of tiger's roar can shock and paralyze

Chameleons (*Chamaeleon*) demonstrate the ability to generate and detect infrasound waves. The representatives of the subfamily *Chamaeleonidae* inhabit the trees and use infrasound for communication − courtship, territorial claims and so on, while the representatives of the subfamily *Brookesiinae* are inhabitants of top-soil and leaf cover; in this situation infrasound waves propagates in all directions and probably are used more for defence against predators.

Chameleon. From travel.guardian.co.uk

There is amazing information from the areas where tsunami took place. In spite of great number of human victims only few animals have been reported dead. The animals escaped and fled the dangerous area long before the tragic event. There is such a hypothesis that probably animals are sensitive to infrasound waves.

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3. HUMIDITY

Water can exist in the atmosphere in three phases: gaseous, liquid and solid. *Vapor* is the gaseous phase of a substance that is normally a solid or liquid. The concentration of water molecules in the gas phase increases during evaporation. An equilibrium is established when the number of molecules escaping from the liquid water equals the number being recaptured by the liquid.

Humidity is the amount of water vapor in a sample of air compared to the maximum amount of water vapor the air can hold at any specific temperature.

Parameters of Humidity

Absolute humidity (a) is the mass (m) of water vapor (grams) per unit volume (V) of moist air (m^3): $a = m/V$.

Partial pressure (e) is defined as the pressure exerted by one gas in a mixture of gases.

The *saturation vapor pressure* (E) is the static pressure of a vapor when the vapor phase of atmosphere is in equilibrium with the liquid phase of atmosphere. The saturation vapor pressure of atmosphere depends on the absolute temperature:

$$\lg E = 9{,}4 - \frac{2345}{T}, \qquad (3.1)$$

where E – saturation vapor pressure (millibars or hectopascals); T – absolute temperature (kelvin).

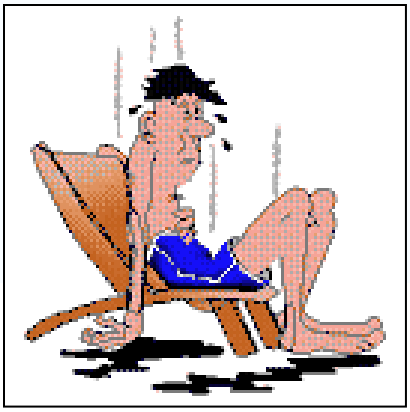
Relative humidity (r) is the ratio of the actual partial vapor pressure of water to the saturation vapor pressure at a given temperature: $r = \frac{e}{E} \cdot 100$.

Vapor deficit (d) is the difference in vapor pressure between saturated and ambient air: $d = E - e$.

Dew point (T_d) is the temperature to which, if unsaturated air is cooled, the water vapor becomes saturated.

Effect of Humidity on Living Organisms

Effect of Humidity on Human Organism. The human organism participates in such heat exchange processes as evaporation (through perspiration), heat convection, and thermal radiation. The first process depends strongly on the humidity: under high levels of air humidity the effectiveness of sweating to cool human body is reduced due to the limitation of the evaporation of perspiration from human surface and the process of maintaining body temperature is rather embarrassing. The combination of high temperature and high humidity of the atmosphere provokes the restriction of heat exchange between blood flows in the body and surrounding air through conduction; this situation causes *hyperpyrexia* − an excessive elevation of body temperature greater than or equal to 41.1° Celsius (106°F). The quantity of blood that reaches the internal organs of the body is decreased and this shortage of the blood leads to various negative consequences such as *heat stroke* (or *hyperthermia*) − an acute condition which occurs when the body produces or absorbs more heat than it can dissipate.



From http://www.allergybegone.com/humidity.html

The optimal levels of relative humidity for an average person in the home ranges between 30% and 65-70%, but the recommended interval is between 30% and 50%.

Effect of Humidity on Microorganisms. The survival of airborne microflora in indoor air depends on the relative humidity: activity of infectious bacteria and viruses is minimized if the range of indoor relative humidity is between 40 and 70 %. Allergenic mites and fungal populations stop their activity under the relative humidity less than 50 %, while these populations reach the maximum at 80 %. Mold spores and dust mites can provoke such human diseases as allergy and asthma.

The most optimal range of the relative humidity of the air is at indoor levels between 40 and 60%.

Effect of Humidity on Animals. Relative humidity plays important role in viability of terrestrial organisms. The air that surrounds the animal maintains less water than its own body. Loss of water by living organism is realised due the final products of metabolism. Supply of organism by water is provided during feeding and drinking. All living organisms have their own ability to adapt to the air humidity. Humidity determines also the distribution of terrestrial animals which remain to be "aquatic organisms" due to their ability to maintain water balance − amphibian, terrestrial crustacean, nematode, molluscs and so on. Usually they inhabit the areas with the relative humidity near 100%.

Effect of Humidity on Plants. Relative humidity determines the rate of transpiration of plants. The fact is that the substomatal leaf space is usually close to saturation level while the vapor pressure of atmospheric air depends on either relative humidity or temperature of the air. If the relative humidity of the surrounding air rises the transpiration rate falls because the water evaporates easier into drier air than into saturated one. Quite the reverse, low level of relative humidity induces the diffusion of water from substomatal leaf space into outer air.

Measurement of Air Humidity

The instrument that is intended for measuring atmosphere humidity is called *hygrometer*. There are several types of hygrometers − psychrometer, hygrometers with organic detectors (hair hygrometer), capacitive hygrometer, condensation or dew point hygrometer, electrolytic hygrometer, radiation absorption hygrometer. We shall discuss here principles of action of psychrometer and those hygrometers which can be used for automatized measurement of atmospheric humidity.

Assmann Psychrometer

The psychrometer is the instrument used to determine air humidity. Assmann Psychrometer was invented in the late 19th century by Adolph Richard Aßmann (1845-1918). It consists of two thermometers – one measuring the air temperature T_a is the dry-bulb thermometer, and the second, the wet-bulb thermometer, has a muslin jacket which stands in a reservoir of water and measures the temperature T_w. The psychrometer is supplied with a fan which draws the air through the tubes; the fan is driven by a clockwork mechanism to ensure a consistent speed. The wet bulb temperature is lower than that of the air due to evaporation of water from the muslin. The relationship between the two thermometer readings can be written as a *psychrometer equation:*

$$e = E_1 - A(T_a - T_w)p_A \qquad (3.2)$$

where e is the water vapor pressure; E_1 the saturated vapor pressure at the temperature of the wet-bulb thermometer; A the psychrometric coefficient ($6.62\cdot10^{-4}$ K^{-1}); T_a the air temperature, T_w the wet-bulb thermometer temperature; p_A the atmospheric pressure (mm Hg or Pa).

The **Model 225-5230 Assmann Psychrometer**
NovaLynx Corporation

Two models are available:

the 225-5230 measures over a range of -30° to +50°C

and the 225-5231 has a range of -20° to +130°F.

Specifications

Range:
225-5230: -30° to +50°C (0.2° graduations)
225-5231: -20° to +130°F (0.5° graduations)

Accuracy: ± 0.1°C with corrections provided

Size: 4" dia x 16" L (100 mm x 405 mm)

Weight/shipping: 3 lbs/10 lbs (1.4 kg/4.5 kg)

From http://www.novalynx.com/225-5230.html

Condensation Hygrometer

Principle of operation of condensation hygrometer (dew point hygrometer) is based on chilling a surface of metallic (silver or copper which have good thermal conductivity) mirror to the temperature at which water on the mirror surface is in equilibrium with the water vapor pressure in the gas sample above the surface. This mirror is covered by inert metal such as gold, iridium, nickel or rubidium to prevent corrosion or oxidation. A thermoelectric semi-conductor element (based on Peltier effect) cools the mirror until dew begins to form. A light emitting diode irradiates the mirror. When the surface of mirror is not covered by dew, the incident light is reflected from the mirror. The reflected light is measured by detector. The formation of dew is accompanied with the light scattering and decreasing reflected light and, correspondingly, the photodetector output. The signal of photodetector is used for control the thermoelectric heating system that maintains the mirror temperature at the dew point.
As the gas sample flows over the chilled mirror, dew droplets form on the mirror surface, and the reflected light is scattered. As the amount of reflected light decreases, the photodetector output also decreases. This in turn controls the thermoelectric heat pump via an analog or igi-

tal control system that maintains the mirror temperature at the dew point. A precision miniature platinum resistance thermometer (PRT) properly embedded in the mirror monitors the mirror temperature at the established dew point.

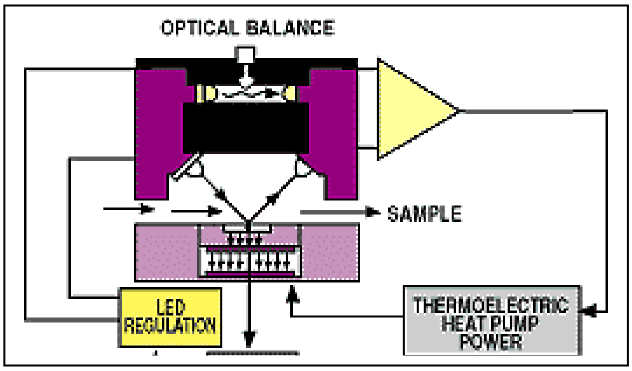


Diagram of Dew Point Hygrometer
(from http://archives.sensorsmag.com/articles/0700/46/index.htm)

Vaisala DEWCAP® Precision SAW Hygrometer DM500

The DM500 is an automatic, continuously controlling condensation hygrometer designed to measure dewpoint temperatures from –75 to +60 °C. It has ±0.2 °C traceable accuracy (optionally ±0.1 °C) with excellent repeatability and fast response time. In addition, the DM500 withstands particulate contamination and distinguishes between frostpoint and dewpoint.

From:
http://www.hygrometer.info/portable_dewpoint_meter.htm

Capacitive Hygrometer

Principle of operation of capacitive hygrometer is based on the humidity depending change of the capacity of the condenser that is formed by a hygroscopic polymer film upon which are placed two porous metallic electrodes. This polymer film absorbs or desorbs water molecules; the change of its volume causes the corresponding change of the distance between the electrodes and capacity of the condenser. In such a way, the change of the capacity is proportional to the change of the relative humidity. The sensor is set upon a square (6 mm× 6 mm) base of thin glass.

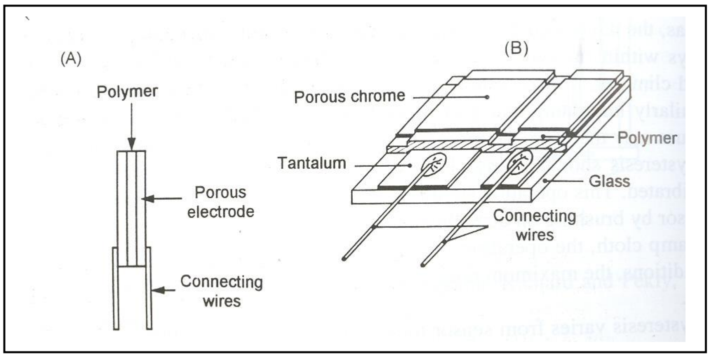


Diagram showing the principle of operation of a capacitive hygrometer (A) and layout of the sensor (B). From: Guyot, 1998.

The advantage of the capacitive hygrometer is compactness, weak dependence of the results of measurements on the external temperature, linearity of response. The hygrometers of such a type are installed in automatic weather stations.

Variable(s) to be measured:	Humidity and temperature	
Name of sensor or instrument:	HMP45A/D Humidity and Temperature Probe	
Type:	HMP45A, HMP45D	
Manufacturer's or Supplier's name:	Vaisala Oyj	
Catalogue sheet No:		
General information		
1.	Principle of operation:	Capacitive polymer sensor, Pt1000/Pt100
2.	Main technical characteristics	
2.1	Application:	Measurement of humidity and temperature
2.2	Measuring range:	0...100 % RH, -40...+60 ?
2.3	Accuracy *(better to be called: Uncertainty)*:	±2 % RH, ±0.2 ?
2.4	Time constant:	15 s (90 % response at 20 ?)

Radiation Absorption Hygrometer (or Gas Analyzer)

The fact is that water vapor demonstrates intense absorption bands in infrared part of spectrum (1.10, 1.38, 1.87, 2.70, 6.30 μm). Estimation of the absorption at these bands makes it possible to measure the air humidity. Principle of action of main gas analyzers are presented in Sections “Eddy Covariance” and “Gas Exchange”.

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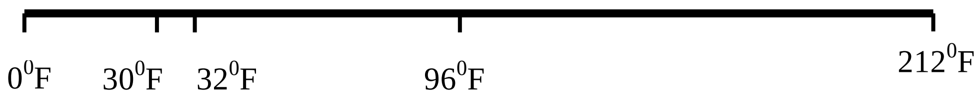
4. TEMPERATURE

Temperature and Temperature Scales

Temperature is a physical magnitude that characterizes the state of thermodynamic equilibrium of macroscopic system. The qualitative estimation of temperature is associated with the notions of hotness and coldness of the object while the quantitative measurement of the temperature is realized with thermometer.

All types of thermometers are based on measurement of the change in some physical properties (volume, length, pressure, resistance, color); each thermometer is supplied with the *temperature scale* calibrated in units called *degrees*. Usually a temperature scale uses two reference temperatures; the temperature difference between these two temperatures is divided into a certain number of degrees depending on the type of temperature scale. We shall discuss three the most important temperature scales that are used today.

In *Fahrenheit scale* several reference points were used. Daniel Gabriel Fahrenheit selected in 1724 as the zero point ($0\ ^0F$) the temperature of a mixture of water, ice and ammonium chloride. The temperature of the same mixture but without salt was estimated as $30\ ^0F$. The temperature of the human body was used as 96°F. The freezing point of water corresponded to 32 degrees Fahrenheit and the boiling point − to 212 degrees. The interval between the two points was divided into 180 parts − the *degrees Fahrenheit* (^0F).



Anders Celsius developed in 1742 the *Celsius temperature scale* (or *centigrade temperature scale*) which was based on 0°C for the freezing point of water and 100°C for the boiling point of water under a pressure of one standard atmosphere. 100 equal divisions between the freezing and boiling points was estimated as the *degrees Celsius* (°C).

The *Kelvin temperature scale* (K) was proposed by Lord Kelvin (William Thompson) in 1848. This temperature scale has an absolute zero − the lowest possible temperature in the universe below which temperatures do not exist, and the triple point of water (the intersection on a phase diagram where the three-phase equilibrium point consists of ice, liquid, and vapour). Zero point is defined as 0 K and corresponds to −273.15 °C, while by definition the triple point of water (273.16 K) corresponds to 0.01 °C.

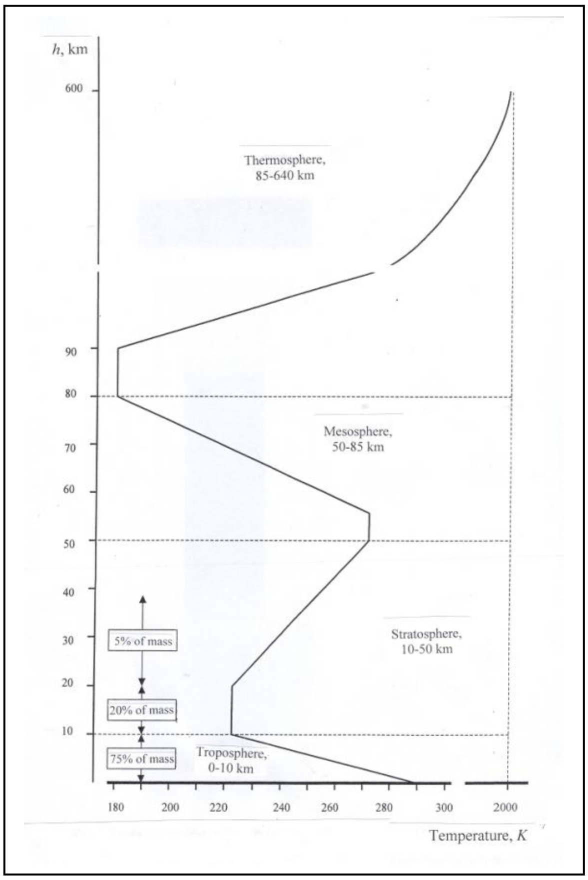
Conversion formulas for temperatures are given as:

Kelvin Temperature Conversion Formulas		
From	**To**	**Formula**
Kelvin	Celsius	$°C = K - 273.15$
Celsius	Kelvin	$K = °C + 273.15$
Kelvin	Fahrenheit	$°F = 9/5(K - 273.15) + 32$
Fahrenheit	Kelvin	$K = 5/9(^0F - 32) + 273.15$
Fahrenheit	Celsius	$^0C = 5/9(^0F - 32)$
Celsius	Fahrenheit	$^0F = 9/5\,^0C + 32$

Atmospheric Temperature

The Earth's atmosphere can be divided according to the dependence of its temperature on the altitude into following layers − troposphere (220 K), stratosphere (260 K), mesosphere (180 K), and thermosphere (2000 K).

Distribution of temperature in atmosphere



Troposhere (from Greek word τρέπω − turning or mixing) is the lowest layer which extends from the Earth's surface to between 8 km at the poles and 16 km at the equator (average depth of the troposphere is about 10 km). This layer is characterized with the vertical mixing of the air due to the heating of terrestrial surface by shortwave solar radiation. Such molecules as carbon dioxide CO_2, methane CH_4, nitrous oxide N_2O and others absorb long-wave radiation of the terrestrial surface and get warm. The temperature of troposphere is decreasing with the altitude due to the horizontal mixing of the air: the warm air masses are expanded, the pressure upon these masses decreases and does work against the opposing pressure of surrounding air. As result the air masses lose energy and their temperature is decreased.

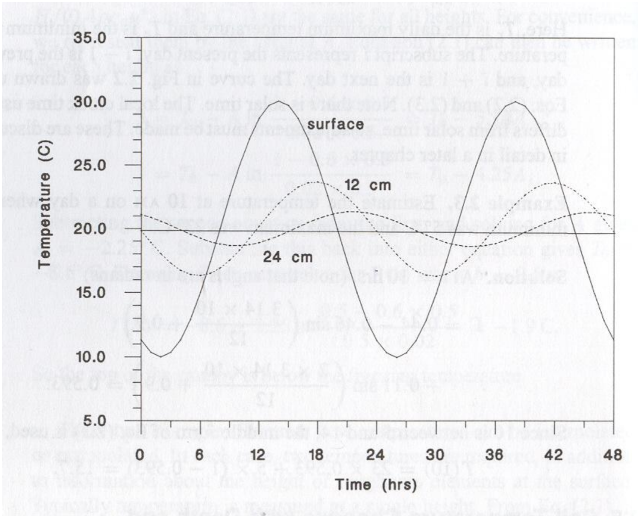
Stratoshere (from New Latin *stratum* − a spreading out) extends from 10 km to 50 km above the terrestrial surface. In the first 10 kilometers of the stratosphere, temperature remains constant with height but then the temperature of stratosphere increases due to the absorption of shortwave solar radiation by ozone layer with maximal concentration at 20-25 km. Ultraviolet component of solar radiation splits oxygen molecules O_2 and produces singlet oxygen O which interacts with O_2 and forms ozone O_3. The temperature of stratosphere increases from about −60°C to −15°C.

Mesosphere (from Greek word μέσος − middle) is a windy and turbulent layer located from about 50 km to 85 km. The temperature in this layer decreases with height from about −15°C to −120°C due to considerable mixing of the air by wind with the velocity 150 m/s.

Thermoshere (from the Greek θερμός − heat) is a layer that begins about 80 km above the terrestrial surface and extends to 600 km high. The temperature of this region increases with height up to 2,000°C due to the absorption of ultraviolet component of solar radiation by small amount of thermospheric gases. But despite the very high temperature this layer can be sensed as cold because an extremely low concentration of air molecules.

Soil Temperature

A typical dependence of soil temperature changes with depth and time demonstrates the sinusoidal character of the diurnal variation of the soil temperature, the shift in maxima and minima with depth and attenuation of diurnal variations with depth.



Hypothetical temperature variations in a uniform soil at the surface and two depths showing the attenuation of diurnal variations and the shift in maxima and minima with depth (after Campbell and Normann, 1998).

The equation that describes the distribution of temperature in the soil as a function of depth *z* and time *t* when the mean daily soil surface temperature $<T>$ is known is the following:

$$T(z,t) = <T> + A(0)exp(-z/D)sin[\omega(t-8) - z/D], \qquad (4.1)$$

where $<T>$ − mean daily soil surface temperature; $A(0)$ – the amplitude of the temperature fluctuations at the surface; D – the damping depth (D = 0,1 m for moist soil and D = 0,03-0,06 m for dry soil).

The range of soil temperature variations at a particular depth is given as:

$$T(z,t) = <T> \pm A(0)exp(-z/D), \qquad (4.2)$$

where the sign “+” corresponds to the maximum temperature and sign “−“ gives the minimum temperature.

The annual soil temperature distribution is similar to the diurnal one but with $\omega = 2\pi/365$ and D is around 2 m.

The damping depth D is determined as

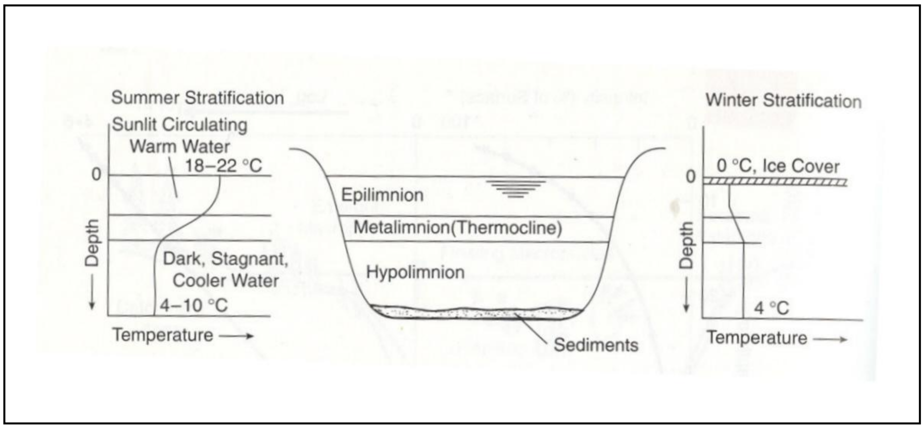
$$D = \frac{z_1 - z_2}{\ln A_2 - \ln A_2}, \qquad (4.3)$$

where z_1 and z_2 are two different soil depths, and $A_1 = T(z_1) - <T>$ and $A_2 = T(z_2) - <T>$ are the corresponding amplitudes of the temperature waves.

Temperature of Water Reservoirs

Thermal regime of water reservoirs such as lakes is determined by high level of thermal capacity of water in comparison with soil; that's why the sharp changes of temperature in the lake water are absent and thermal conditions are more stable. In lakes and in slow-flowing rivers the surface layers of water are heated by solar radiation more quickly than the water in the depth. In addition, the upper layers are well mixed by the wind. More warm layers have less density and overlies the more cold and dense layers.

The upper warm layer is called the *epilimnion,* while the lower cold layer is called the *hypolimnion*. Between these two layers is a third layer − so-called the *metalimnion* which is characterised by strong vertical temperature gradients.



Thermasl stratification of a deep lake (After Henry and Heinke, 1996)

As the whole, the thermal regime in the lake water depends strongly on the influence of environmental and meteorological factors, the size, shape and depth of the water reservoir, the season.

During summer, the solar heating and spring wind mixing induces the formation of a less dense water layer. Under such conditions the epilimnion is mixed continuously and phytoplankton grows activily.

In the winter, lakes freeze and ice covers the surface. Water which has maximum density at 4 ^{0}C but not at 0^{0}C − the temperature of ice formation. In such a way, this ice is able to float on the surface despite its state and play role of insulating layer between cold air and more warm water. The presence of such an ice cover makes it possible to conserve heat inside the lake.

The rivers are characterised by more dynamic temperature changes then the more deep lakes.

Effects of Temperature on Living Organisms

Living organisms inhabit the Earth's regions with different temperature range. The coldest place is Antarctica, where the temperature can reach −89.2 ^{0}C; the highest temperature is about 80 ^{0}C in desert areas.

The upper thermal limit for animals and plants is about +50 ^{0}C and for thermophilic bacteria is about 90 ^{0}C. High environmental temperatures provoke the overheating of the body and *hyperthermia* − an acute condition when the body produces or absorbs more heat than it can dissipate. Exceeding ambient temperature the limit 41.5-42.5 ^{0}C can lead to *heatstroke* − a severe and often fatal condition produced by cessation of sweating and exposure to excessively high temperatures.

The lower limit for aquatic animals is determined by the freezing point of sea water at −1.86 ^{0}C. The wood frog, *Rana sylvatica,* is capable to withstand temperatures as low as -8°C, with 65% of its body water converted to ice. Terrestrial large polar animals and birds can tolerate to the temperatures about −60 ^{0}C.

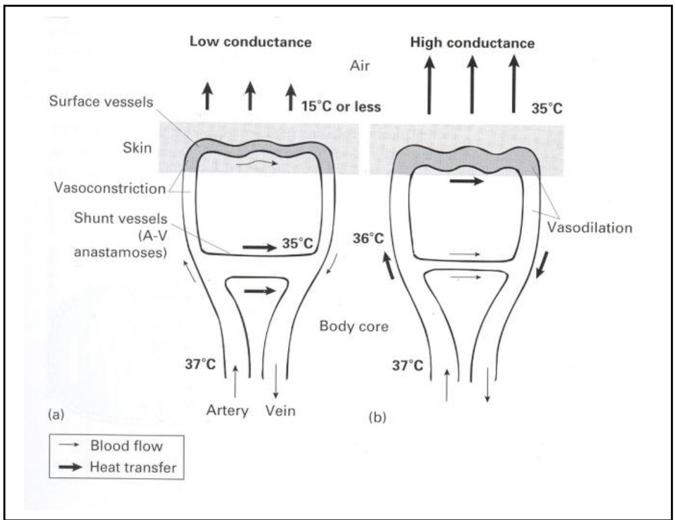
It is necessary to mention the temperature change during the course of year that can vary from −70 ^{0}C in winter to +36.7 ^{0}C in Siberia or by less than 0.2 ^{0}C in the Antarctic ocean water.

Animal Adaptation to Extreme Temperatures

All animals can be classified as endptherms and ectotherms. An organism that have a body temperature principally dependent on their internally generated metabolic heat is called *endotherm.* An organism that have a body temperature principally dependent on external heat sources (Sun or heated substrate) is called *ectotherm.*

Vasoconstriction and Vasodilation. One of the effective way to counteract the extreme temperatures is regulation of surface temperature through physiological thermoregulation by peripheral blood flow control which is realised by shunting blood either tom or away from the skin: the blood vessels of the skin get narrow while the vessels of internal organs are widened.

The role of blood flow to the skin in regulating the heat conductance of the body surface and hence heat loss. Vasomotor control of peripheral arterioles and arteriovenous (A-V) anastomoses is mainly responsible for shunting blood either (a) to or (b) away from the skin (after Willmer et al.,2000)



This process of thermoregulation through the contraction (relaxation) of blood vessels is called *vasoconstriction* (*vasodilation*).

Thermal Insulation. The layer of fur or fat plays an important role in heat conduction between the body of animal and its surrounding. The less thermal conductivity of the fur the more insulation of it. In such a way, insulation properties of animal and its ambient are determined with the conductivity of biological materials and environmental components.

The fur of boreal mammals is an effective means against the cold temperature: the length and density of hair cover changes during a year: the winter coats are thicker and better insulating than summer coats. Heat energy transfer through thermal conduction depends strongly on the thermal conductivity of hair coat which is filled up by air. The conductivity of air is small and varies from 0.0237 W/m·K (−10 ^{0}C) to 0.0277 W/m·K (50 ^{0}C). These small values of thermal conductivity of air determine high insulation properties of hair coat of the animals.

The thickness of fur coat can reach 6 cm for polar bear and 5-10 cm for muskox.

The values of conductivity of of biological and other materials are presented in Table 4.1.

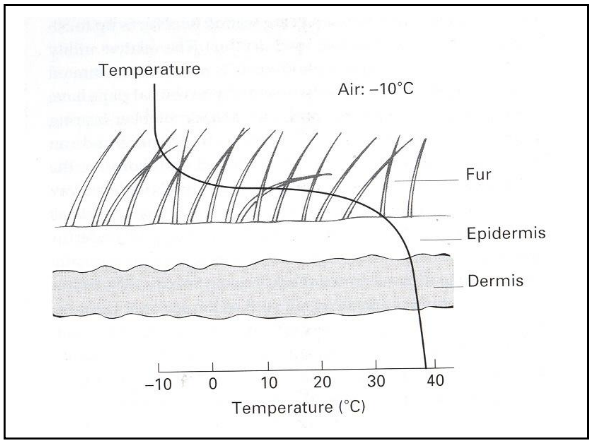
Muskox (from www.quantum-conservation.org)

The layer of fat under the skin can help to keep arctic animals warm in cold weather. The thickness of fat layer of polar bear is about 11 cm. Walrus has a layer of fat about 5-7 cm that acts as insulation.

4.1. Conductivity values of biological and other materials

Material	Conductivity, W/m·K	Temperature, °C
Air (dry)	0.0237	–10
«	0.0243	0
«	0.0250	10
«	0.0257	20
«	0.0264	30
«	0.0270	40
«	0.0277	50
Water	0.565	0
«	0.599	20
«	0.627	40
Ice	1.6-2.9	
Snow (dry)	0.21	
Soil (dry)	0.14	
Fat (cow)	0.222	
Fat (pig)	0.159	
Blubber (Minke whale)	0.200-0.280	
Blubber (Harp seal)	0.190-0.010	

The angle of inclination of hairs regulates the thermal gradient from ambient temperature to skin surface temperature. For example, the change of the temperature from +11.0 ^{0}C to −24.5 ^{0}C induces the increasing the angle of hair inclination from 28^0 to 63^0 for Ukrainian race of cattle.

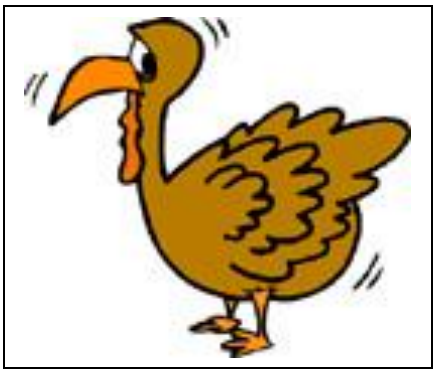


The temperature gradient across the surface of a high-latitude mammal; the gradient is largely across the highly effective fur, and skin surface temperatures are close to core temperatures (after Willmer et al., 2000)

The birds are able to fluff their feathers and to trap insulation layer of air in the feathers. So, such a system of thermal insulation ensures the penguins survival in Antarctic water, where the temperature is cold as −2.2 ^{0}C and rarely reachs +2 ^{0}C.

Thermogenesis. This is a high-frequency reflex process of heat production in cold environment which is realised through *shivering* − muscular activity, or by metabolism of special *brown fat cells* − activation of fermentative systems that is accompanied with substantial heat output. Thermogenesis is used by the Indian phyton female during incubation period; rhythmical contraction of the muscles raises the temperature of body and the egg temperature to 7-8 ^{0}C above ambient. Shivering thermogenesis is used by some moths, beetles, dragonflies, wasps and bees.

Shivering (from www.thefreedictionary.com)



Non-shivering thermogenesis occurs in small mammals such as rodents, bats, rabbits and insects such as bumble-bees.

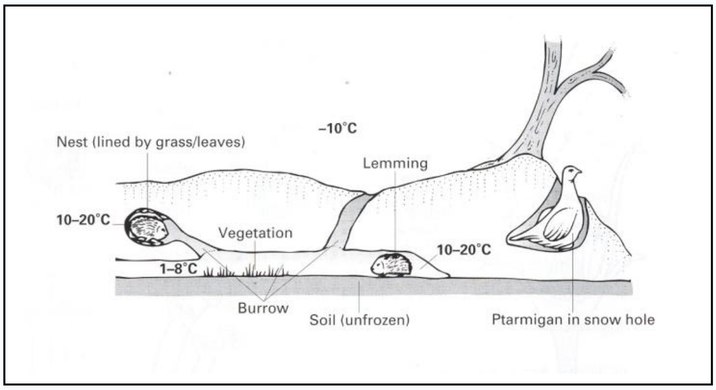
Huddling and Aggregation. The ability of polar inhabitants such as penguins, seals, muskoxen to cluster together prevent the negative effects of the temperature drops up to –50 °C and strong wind with the speed over 160 km/h. Penguins form dense huddles about several thousand (up to 6000) individuals, that reaches a biomass of 100 tons. Such a huddling makes it possible to save as much as 80 % of the heat loss in comparison with an isolated bird.

Huddling behavior in Emperor Penguins (from Gilbert et al., 2006)

Musk oxen live in herds up to 100 individuals in winter, seals can form herds on the sea beaches about 1000-1500 heads. The process of huddling and aggregation is typical for snakes (python, anaconda, boa, adder, red-sided garter) and lizard during cold nights; insects are aggregated in the evening to slow down the loss of heat. Small birds (sparrows, hoopoes and others) demonstrate the ability to be clustered in response to low ambient temperatures.

Burrowing is one of the optimal way to escape extreme ambient temperatures. The representatives of burrowing animals are well-known rabbit, groundhog, a number of fish, amphibians, reptiles, birds, numerous invertebrates including insects, spiders, scorpions, sea urchins, clams and worms. The burrows are constructed in various types of substrate such as soil, sand, wood, rock. The length of a single burrow can vary from a simple tube of several centimeters to a developed network of interconnecting tunnels and chambers with the total length about thousands meters. It is known that a single groundhog burrow occupies a full cubic meter, displacing 320 kilograms of soil. The internal temperature of air in the burrow is kept constant. So, the burrow of deer mice in Nevada region has constant internal temperature about 26 ^{0}C while the temperature of external air varies from 16 ^{0}C to 44 ^{0}C.

The problem of realization of thermal insulation though burrowing is especially actual in Arctic regions. The burrows beneath the snow cover can escape the cold: the temperature within snow reaches 10-20 ^{0}C while the ambient temperature is −10 ^{0}C. The typical representatives of subnivean habitat are lemming, ground squirrel, rock ptarmigan. Even large animals like polar bears use the snow dens to wait till the coldest period of winter is over.



Microclimate within snow − the subnivean habitat (from Willmer et al., 2000)

Coloration. The color of the animal corresponds the spectral reflectance of its surface. The animals with white and pale surface reflect the solar radiation more intensively and warm more slowly in comparison with dark-colored animals. Some animals and insects have both white and black parts of their bodies that makes it possible to regulate the absorption of short-wave solar or long-wave terrestrial radiation by their surfaces. Some species (frogs, chameleons, lizard) are able to change their reflectance (coloration) according to thermal need.

For example, laboratory experiments demonstrated, that a South American frog, *Bokermannohyla alvarengai*, kept in the dark or at lower (20°C) temperature had darker skin colour while the frogs kept in the light or higher (30°C) temperature had skin colour of a lighter hue. In such a way, colour change is induced by the increase in incident solar energy and in anticipation of changes in body temperature.

Digital images of a South American frog, *Bokermannohyla alvarengai*, taken under various circumstances. (A) A cryptically coloured individual in the field, (B) a non-cryptic individual in the field, (C) a darkly coloured cool (18°C) frog at the beginning of Series III experiments, and (D) the same frog as in C 1 h later after reaching 28°C. Note the dramatic colour differences between individuals in the field under varying circumstances (A,B) and within the same individual (C,D) at different body temperatures (after Tattersall et al., 2006).

Insects are able to realize the thermoregulation through the reflectance (color) also. Small insects that are active at dawn and dusk have dark coloration, while those insects that are active in middle of the day must have bright or pale color that corresponds to good surface reflectance. Those insects which are living near ground surface, usually have black or brown coloration because the long-wave radiation of the Earth's surface dominates in the process of their warming.

The dark coloured feathers of back surface of penguins provides the warming of these birds by solar radiation.

Thermoreception

Thermoreception is the perception of temperature changes by organism, which is accompanied by generation of electric impulses which are transferred to the central nervous system.

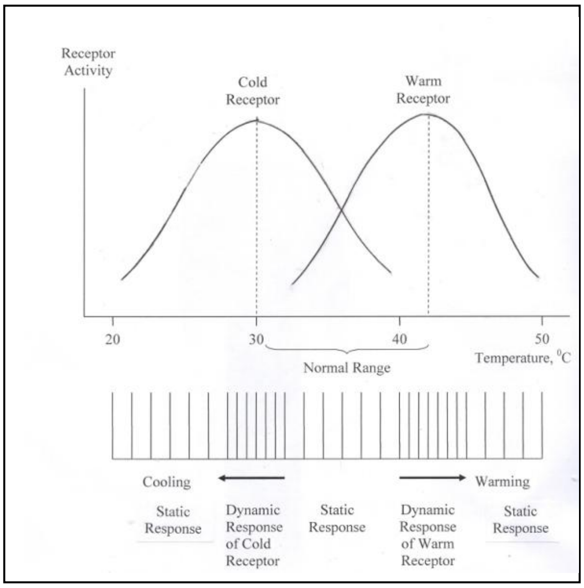
Insects have thermoreceptors on their legs or antennae; fish − on the skin, lateral line and in the brain; birds − in the skin, on the tongue and bill.

Mammals detect the environmental temperature by skin thermoreceptors; there are two types of thermoreceptors − *warm receptors* that detect temperatures above body temperature and *cold receptors* that detect temperatures below body temperature.

A typical density of the human skin thermoreceptors is about 5-10 receptors per cm^2. The density for cold receptors in the skin is 5 times greater than the density of warm receptors. Cold receptors are located at upper lip, nose, chin, chest, fingers; warm receptors − at fingertips, nose, elbows.

A single cold fiber is in the state of *static response* at constant temperature it genberates the discharge of steady frequency. Usually the static activity is observed at temperature range between 20 ^{0}C and 35 ^{0}C with maximum at about 22-27 ^{0}C for cold receptors and between 30 ^{0}C and 50 ^{0}C with maximum at 44.5 ^{0}C for warm receptors.

Sudden cooling to a lower temperature provokes the *dynamic response* of the cold receptors − a transient increase in frequency which achieves maximal level at 27-31 ^{0}C; further increases in temperature returns receptor to a level of static response.



Warm receptors respond to sudden warming by frequency increase with maximum at 44.5 ^{0}C ; further increases in temperature results the level of static response.

Sudden change of temperature induces a transient increase in frequency; if new temperature is maintained stable, the frequency decreases to a level of static response.

The principal properties of thermoreceptors – a steady-state discharge at constant skin temperature; increasing or decreasing the pulse frequency under temperature changes; insensitivity to non-thermal stimuli.

Thermal Sensitivity of Animals

Thermotaxis is the movement of a living organism toward or away from a source of heat.

Many microorganisms and animals demonstrate strong behavioral response to changes in temperature (thermal gradients) and direction of thermal stimuli.

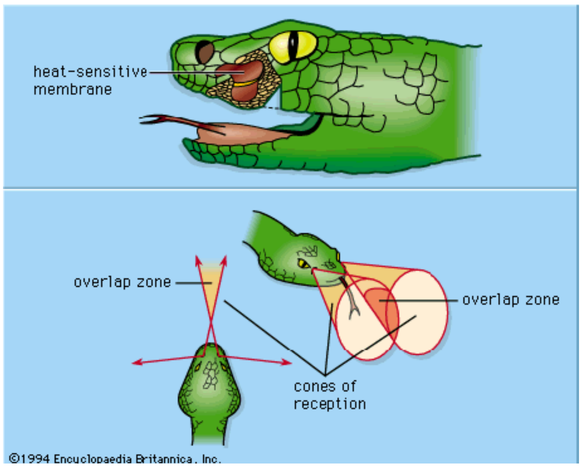
Such organisms as nematode *Caenorhabditis elegans* which lives in temperature soil environment, larvae and adults of *Drosophila* exhibit thermotaxis.

Many aquatic organisms (algae, protozoa, fish) provide daily vertical migrations in water medium, transferring themselves into warm regions for the night and returning to cooler layers of water for the day. There is such an opinion that this migration can be explained by a thermoregulatory strategy allowing aquatic organisms to lower their metabolic rates in cold waters and to conserve energy.

Snakes. Rattlesnakes (*Crot alus*) and relatedc species of pit vipers (*Viperidae*), boas (*Boidae*) and pythons (*Pythonidae*) are characterized with extremely thermal sensitivity. These snakes have *pit organ* that are located between the eye and the nostril on each side of the head. For example, the pit organ of rattlesnakes contains a membrane with an area about 3×4 mm^2 and 10-15 μm thick that is suspended into an air-filled cavity. About 3,500 neurons are embedded in this membrane. Pit organ responds to rate of ambient temperature change by increasing the rate of action potentials. Such a system plays role of infrared detector with thermal sensitivity 0.002 ^{0}C that help snake to find the heat source – a warm-blooded prey during the movement.

By comparing information from both pits, the snake can determine direction and distance of the prey.

The pit organ of rattlesnake, *Crotalus willardi obscurus* (from http://en.wikipedia.org/wiki/Crotalinae)



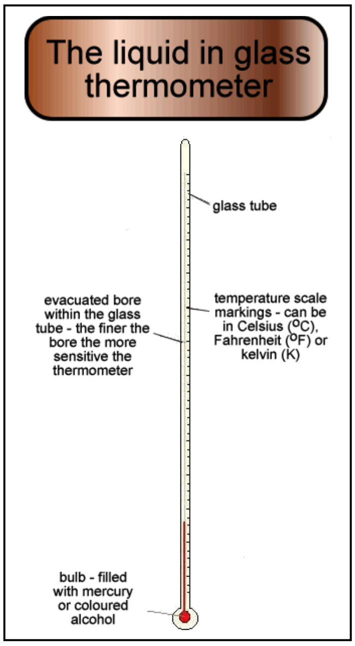
Detection of direction from heat source by rattle-snake (from httpwww.britannica.comebarticle-64743thermoreception)

Brush-Turkey (*Alectura lathami*) is a widespread bird found in eastern Australia. A typical group of these communal birds build large (4 m of diameter and 1.5 m high) nest on the ground made from leaves or sand or other combustible materials. The clutch (about 16-24 eggs) are heated by the composting mound; the constant (33-35 0C) temperature of the clutch is regulated by the male through adding or removing material.

Measurement of Temperature

Liquid-in Glass Thermometers is based on expansion of liquids. It is known that the volume of material (solid or liquid) changes with temperature: the change in volume ΔV at constant pressure is proportional to the original volume V and the change in temperature ΔT as $\Delta V = \beta V \Delta T$, where β – the coefficient of volume expansion. In this thermometer the liquid rises inside a capillary column because the coefficient of volume expansion of liquids is much higher than that of glass: $1.81 \cdot 10^{-4}$ (^{0}C)$^{-1}$ – mercury; $10.6 \cdot 10^{-4}$ (^{0}C)$^{-1}$ – alcohol; $9.16 \cdot 10^{-4}$ (^{0}C)$^{-1}$ – toluene; $2.5 \cdot 10^{-5}$ (^{0}C)$^{-1}$ – glass.

Liquid-in-Glass Thermometer consists of *bulb* – the reservoir for containing liquid; *stem* – the glass tube having a capillary bore along which the liquid moves with changes of temperature; *scale* – an engraved or etched scale with well-defined, narrow lines graduated in degrees of Celsius.

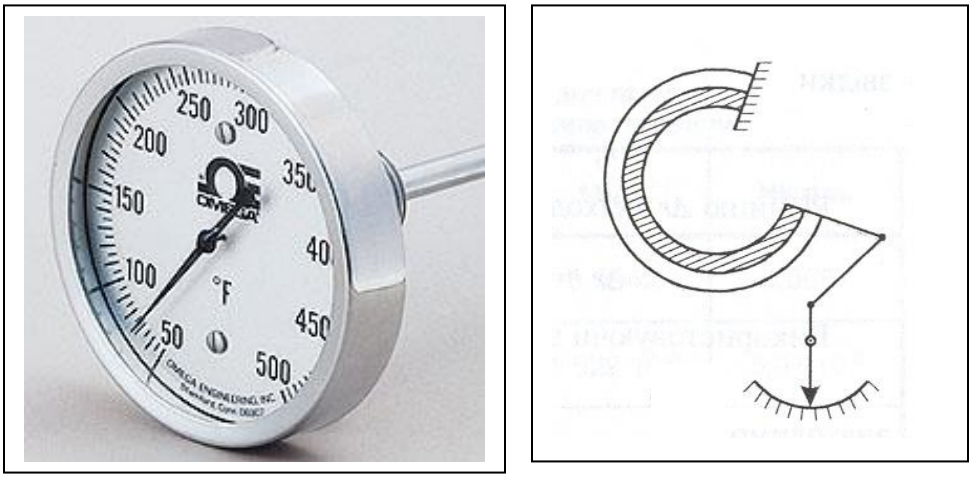


Liquid-in-Glass Thermometer.
(from http://www.cyberphysics.pwp.blueyonder.co.uk/topics/heat/ThermometerLIG.htm)

The advantages of liquid-in-glass thermometer are portability, low cost, compatibility with most environments, wide range of temperatures which depends on the liquid.

The most widely used liquid in this type of thermometers is mercury. It is a liquid material that doesn't deteriorate or adhere to the glass. The temperature range of mercury thermometers is from –38,83 ^{0}C to +356,7 ^{0}C. For measurement of low temperature such liquids as alcohol or toluene are used: the melting points of alcohol is –114 ^{0}C, and –95.1 ^{0}C for toluene. But these liquids are chemically less stable than mercury and can be decomposed under sunlight.

A *Bimetallic Thermometer* uses thermal expansion of solids, particularly on application of the bi-metallic strip that consists of two different metals which have different coefficients of expansion and expand at different rates under external temperature. Usually such pairs of metals as steel-copper or steel-nickel are used. One end of the strip is fixed, and the another one is related to the indicator. As soon as both metals have different expansions the change of temperature induces the bending of the bi-metallic strip. The displacement ΔX of the free end depends on the change of temperature Δt as $\Delta X = K \Delta t$, where K is coefficient of proportionality. This device is characterized with linear dependence of the displacement on the temperature.



Bi-metallic thermometer
http://www.omega.com/ppt/pptsc_lg.asp?ref=A_R_DIALTEMP&Nav=

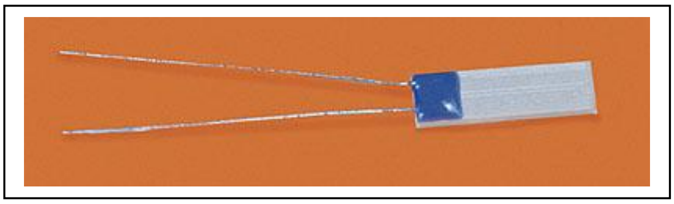
Resistance Thermometer is based on the ability of some materials to change their electrical resistance with changing temperature. There are two main types of these thermometers − metallic devices which are called *thermoresistors*, and semiconductor devices − *thermistors.*

The resistance of metal depends on the temperature linearly according to the following equation

$$R = R_0\,(1 + \alpha \Delta T), \qquad (4.4)$$

where R is the resistance at temperature T; R_0 is the resistance at temperature T_0; α – thermal coefficient of metal; $\Delta T = T - T_0$ (where T_0 = 273.15 K = 0 ^{0}C).

The most widely used material for thermoresistors is platinum. We have described platinum resistor HMP45D previously, in Section “Humidity”, which can be used for measurement either humidity, or temperature. Platinum resistors consists of a fine wire (diameter less than 0.1 mm) covered with a layer of glass or ceramic. Platinum is characterised with high level of stability under influence of corrosion or action of aggressive chemicals. The platinum resistance changes by about 0.3 % for each temperature change of 1 K. The temperature range of platinum thermoresistor is from −50 ^{0}C to 550 ^{0}C.



Platinum thermoresistor
(from http://www.omega.com/pptst/TFD_RTD.html)

The resistance of semiconductors decreases with temperature as follows

$$R = ae^{b/T}, \qquad (4.5)$$

where *a* and *b* are constants depending on the material of semiconductor; *T* is the temperature in kelvins.

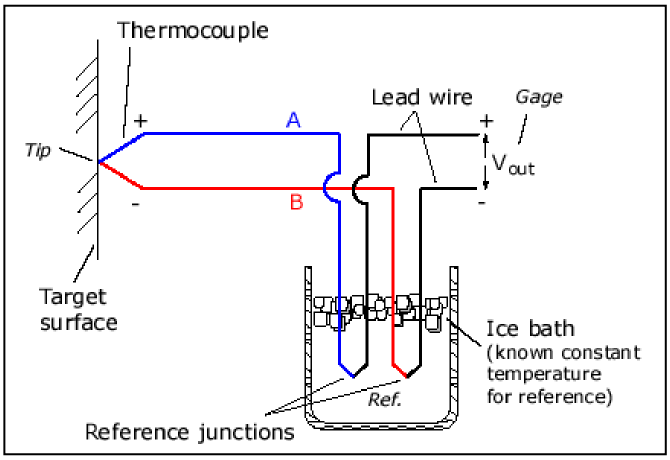
Thermistors are fabricated from oxides of various metals (nickel, manganese, cobalt, copper). The size of thermistor can reach 0.2 mm. Typical accuracy of temperature measurement of these devices is ± 1 ^{0}C; the temperature range is from –50 ^{0}C to 100 ^{0}C .

Thermocouples are thermoelectric devices consisting two different metals welded together at each end so that a potential difference generated between the two junctions is a measure of the temperature difference between the junctions. One junction is at the temperature to be measured; the another one is held at a fixed lower temperature.

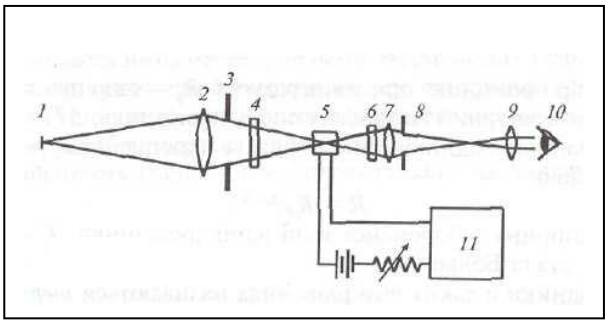
Typical used thermocouples consist of such metals or alloys as copper-constantan, chromel-alumel, chromel-constantan, iron constantan, platinum-platinum/rodium (10%). These devices are cheap, can measure a wide range of temperature (for example, Chromel-Alumel – from – 200 ^{0}C to +1200 ^{0}C; Iron-Copper – from –40 ^{0}C to +750 ^{0}C; Copper-Constantan – from –200 ^{0}C to +350 ^{0}C.

The main disadvantage is low accuracy: it is difficult to achieve system errors less than 1 ^{0}C.

Principle of operation of thermocouplke (from www.efunda.com)

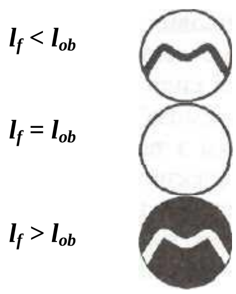


Optical Pyrometry is based on the non-contact measurement of the temperature of an object through estimation of its emissivity − the ratio of energy radiated by the material to energy radiated by a black body at the same temperature. An instrument that measures the temperature by means of pyrometry is called *optical pyrometer*. It consists of source of radiation, calibrated lamp, filter with narrow band of transmission, and detector.



Optical pyrometer: 1 − source of light; 2 − lens; 3 − diaphragm; 4 − filter; 5 − incandescent lamp; 6 − red filter; 7 − lens; 8 − diaphragm; 9 − ocular; 10 − observer

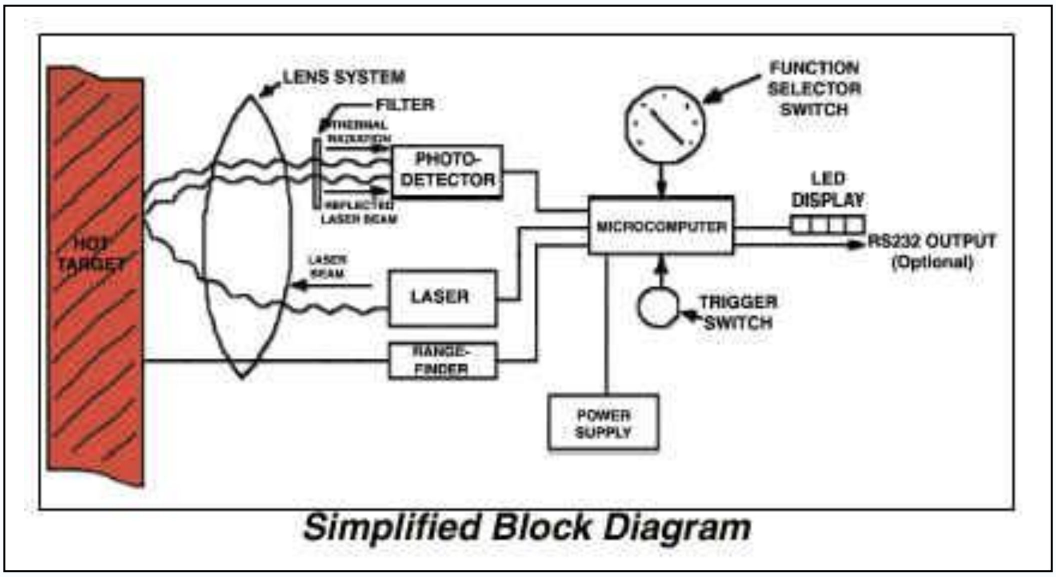
The procedure of measurement is based on comparison the brightness of the object l_{ob} under measurement with the brightness of the wire filament l_f of the lamp. The brightness and temperature of the wire is regulated by adjusting the electric current that passes through the wire. The temperature is measured when the brightness of object and filament are equal.



Infrared Thermometer determines surface temperature through measurement surface radiance from equation

$$L_e = \frac{\varepsilon \sigma T_S^4}{\pi}, \qquad (4.6)$$

where ε – the surface emissivity ($0<\varepsilon<1$); σ – the Stefan-Boltzmann constant ($5{,}67 \cdot 10^{-8}$ Вт·м$^{-2}$ ·К$^{-4}$); T_s – the surface temperature (K).



Infrared Laser Thermometer
(from httpwww.mikroninfrared.comproductsprocessQuantum-I.htm)

The Mikron Quantum I Portable Laser IR Thermometer

Temperature Range
MQ1310(C)-2A..... 450 - 932°C (1.65 μm)
MQ1310(C)-2B..... 450 - 1260°C (1.65 μm)
MQ1310(C)-1A..... 740 - 1538°C (0.9 μm)
MQ1310(C)-1B... 1100 - 3000°C (0.9μm)

Accuracy ±3 °C

Repeatability ±1 °F or ±1 °C

Dimensions (15.5cm)H, (8.4cm)W, (10.4cm)L

Resolution of display 1 °F or 1 °C

Infrared laser thermometer contains an optical system with lens and filter which directs laser radiation on the target and focuses infrared radiation flux on photodetector. The detector is a thermal sensor that converts infrared radiation in electrical signal proportional to the intensity of radiation. A filter makes it possible to pass only the desired wavelength. Device is supplied with microcomputer for elaboration of the results of measurements and power source.

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5. SOLAR RADIATION

Characteristics of Sun

The *Sun* is the star of our solar system which supports all life on Earth and drives the Earth's climate and weather. *Solar radiation* is radiant energy by the sun, particularly electromagnetic energy.

Sun (from www.astropix.com)

The principal characteristics of the Sun are:

Mean distance from Earth 149.6×10^6 km;
Mean diameter 1.392×10^6 km;
Mass 1.988×10^{30} kg;
Density 1.408 g/cm³;
Surface temperature 5785 K;
Temperature of corona 5 MK;
Core temperature ~13.6 MK;

The main parameters of Sun are intensity, spectral composition, periodicity of solar activity.

Intensity of Solar Radiation

Intensity is the magnitude of energy per unit of area. Intensity of solar radiation is proportional to *irradiance* − the power of electromagnetic radiation incident on the surface, per unit area. The SI units for this quantity is watts per square meter (W/m^2),

The power that is received by Earth from the Sun is $1.74\cdot10^{17}$ W.

The annual mean energy received can be calculated as:

$$E = Pt = 1.74\cdot10^{17}\text{ W}\cdot365\text{ days}\cdot24\text{ hours} = 1.524\cdot10^{18}\text{ kWh}.$$

Intensity of solar radiation on the Earth's surface is:

$$I = P/A = (1.74\cdot10^{17}\text{ W}/1.27\cdot10^{14}\text{ m}^2) = 1370\text{ W/m}^2,$$

where $A = \pi R^2 = 3.14\cdot(6.37\cdot10^6\text{ m})^2 = 1.27\cdot10^{14}\text{ m}^2$ is the area of the Earth's surface as disk; R is radius of the Earth.

As soon as the Earth rotates the whole surface which is radiated by the Sun is four time as great as the disk

$$A_{sp} = 4\pi R^2 = 5.08\cdot10^{14}\text{ m}^{2.}$$

Thus the mean intensity of incoming solar radiation is

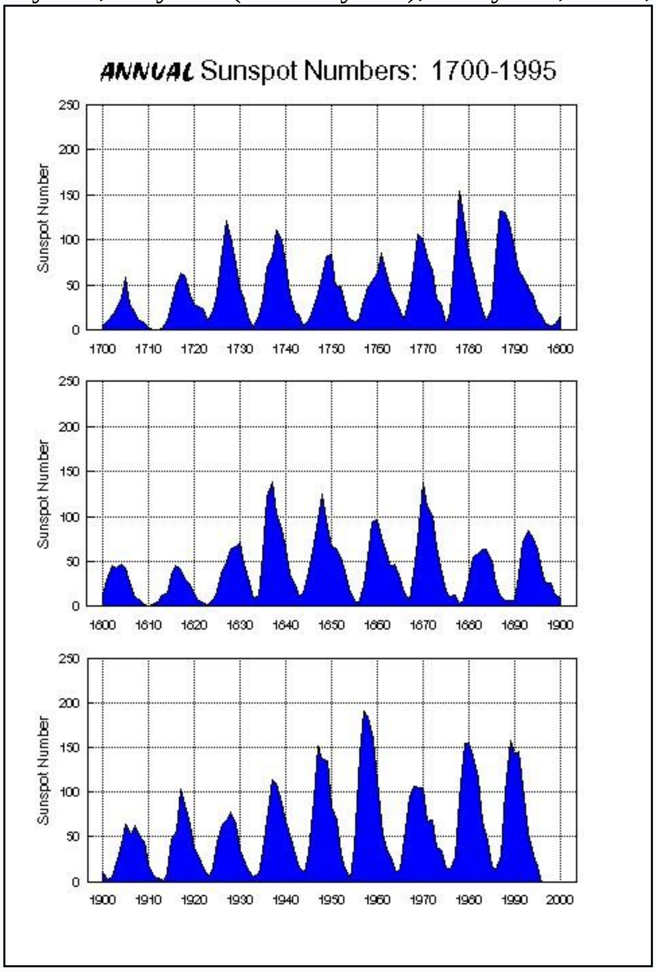
$$I = P/A = (1.74\cdot10^{17}\text{ W}/5.08\cdot10^{14}\text{ m}^2) = 342\text{ W/m}^2.$$

Actual mean intensity varies from 250 W/m^2 (subtropical regions) to 80 W/m^2 (cloudy regions). The level of solar intensity depends on the time of year, time of day, latitude, the distance between the Sun and the Earth, attenuation of solar radiation by the Earth's atmosphere.

In Ukraine mean solar intensity varies from 185-215 W/m^2 (Northern part) to 115-145 W/m^2 (Southern part).

Periodicity of Solar Radiation

Cyclic changes of solar activity are known as *solar cycles*. There are 11-years-cycle which is characterized by cyclic increase and decrease of sunspots during period of about 11 years; 22 years, 87 years (70-100 years), 210 years, and 2,300 years cycles.

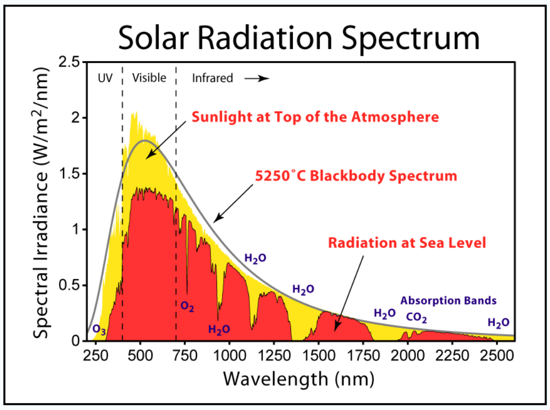


Sunspots during period of time from 1700 till 1995 (from www.windows.ucar.edu/tour/link=/sun/activity/solar_cycle.html)

Spectral Distribution of Solar Radiation

The entire frequency range of electromagnetic waves is called the *electromagnetic spectrum*. Solar spectrum occupies the range 200-5000 nm and consists of three important bands – *ultraviolet* (UV), *visible* (VIS) and *near-infrared* (NIR). UV part of spectrum occupies 5 %, visible – 35 %, and infrared – 60 % of total solar radiation.

The spectral range of ultraviolet radiation is 100-400 nm; visible – 400-700 nm; infrared – 700-5000 nm.



Distribution of Solar Radiation (from httpupload.wikimedia.org wikipediacommons44cSolar_Spectrum.

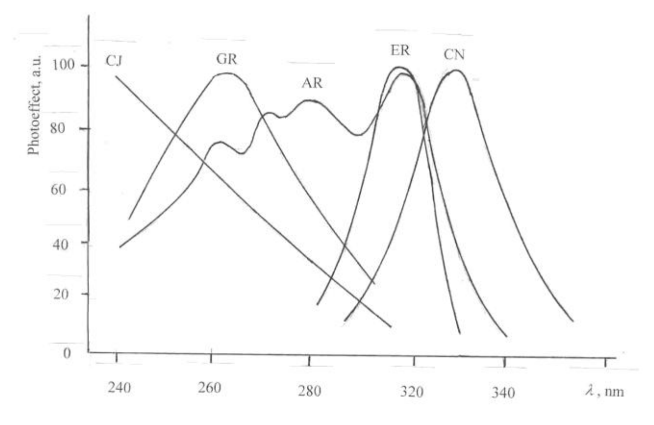
Effect of Solar Radiation on Living Organisms

Effect of Ultraviolet Radiation. Ultraviolet range can be divided into three parts: UV-A (400–315 nm), UV-B (315–280 nm), and UV-C (< 280 nm). It is considered that UV-C radiation is the most hazardous for living organisms; UV-B may provoke specific but not always dangerous effects in living organisms; UV-A is safe radiation.

Solar ultraviolet radiation is characterised by a substantial impact on human health, terrestrial plants, aquatic ecosystems, and air quality.

The primary organs of humans and animals which are exposed by natural UV-B radiation are eyes and skin. Thus, UV-B radiation induces the cataracts, erythema, aging of the skin, photodermatoses and skin cancer. The exposure of unprotected eyes to solar radiation (mainly UV-B and UV-C) provokes the photokerato-conjunctivitis ("snow blinding"). The positive effect of this radiation is the formation of vitamin D in the skin that is important for the maintenance of bone tissue. It is necessary to mention the effect of UV-B radiatuion on the immune system.

Spectral distribution of biological effects in ultraviolet part of spectrum:
CN – cancerogenic effect;
ER – erythema; AR – anti-rickets effect;
CJ – conjunctivitis; GR – germicidal effect



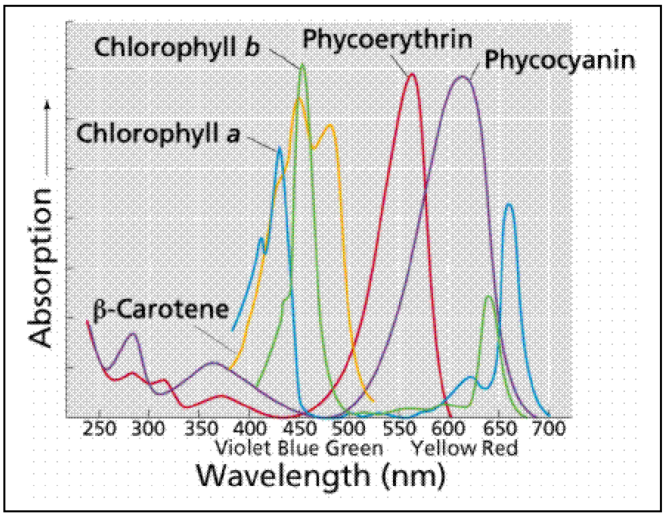
Solar UV-B radiation provides the effects on physiological and developmental processes of plants and algae, including the changes in plant morphology, phenology, biomass accumulation, inhibition of photosynthesis, DNA damage.

Solar UV-B radiation demonstrates strong effects on inhabitants of aquatic ecosystems. It inhibits the motility of phytoplankton and its spatial orientation, causes damage to early development stages of fish, shrimp, crab, amphibians, impair larval development. The photosynthesis of red, brown and green algae is inhibited by UV-B radiation.

Energetic UV-B radiation can break the bonds of atmospheric gases such as ozone, nitrogen dioxide, formaldehyde, hydrogen peroxide, nitric acid producing highly reactive atomic and molecular radical species (O, H, OH, HO_2) that are responsible for adverse effects on human health and air quality.

Effect of Visible Radiation. Electromagnetic radiation in the range of wavelengths from about 400 to 700 nm is called *visible radiation*; a typical human eye is sensitive to this part of spectrum. The spectral range of solar radiation from 400 to 700 nm that is used by terrestrial and aquatic plants and algae during photosynthesis is called *Photosynthetically Active Radiation* (*PAR*).

Solar visible radiation induces certain photobiological reactions in living organisms. Principal photobiological reactions that are related with the environment are presented by photosynthesis, photoperiodism, photomovement, photosensitization. Solar visible radiation plays an important role in viability of living organisms which have special pigments that able to absorb solar radiation.



Absorption spectra of the most important pigments (from httpupload.wikimedia.orgwikipediacommons44cSolar_Sp)ectru

Photosynthesis

The photobiological reaction of green plants and algae by which carbohydrates are synthesized from carbon dioxide and water using light as an energy source is called *photosynthesis*; oxygen is released as byproduct of this reaction.

Photosystems, PSI and PSII are principal functional units which provide photosynthetic activity of plants and algae. These systems contain about 300 molecules of pigments which can absorb photons, but only one chlorophyll molecule of such photosystems can transform absorbed energy to photochemical reaction. This molecule of chlorophyll is defined as *reaction centre* of photosystem while the others – as *antenna*. The transfer of the light absorbed energy to reaction centres of photosystems is accompanied with excitation of chlorophyll molecule P_{680} and transfer of electrons on upper energy level. Excited molecule P^{*}_{680} transfers electrons to acceptor – pheophytin *Ph*, then to primary quinone acceptor, Q_A, secondary quinone acceptor, Q_B, plastoquinine (*PQ*) pool, iron sulfur protein, FeS_R , cytochrome, b_6, cytochrome, *f*, plastocyanin, *PC*, and *PSI* where the light energy transfers the electrons from chlorophyll molecule P_{700} to primary electron acceptor, A_0, A_1, three iron-sulfur centres, ferredoxin, *Fd*, which forms complex with flavoprotein ferredoxin-*NADP* reductase, *FNR*, for the formation of *NADPH*.

In addition, absorbed energy can be released as heat or radiation process such as fluorescence. At room temperature the chlorophyll fluorescence originates from *PS II*; the contribution of *PSI* to fluorescence is significant only in the long-wavelength part of spectrum (740 nm). Variable fluorescence is related mainly to *PSII* while excitation transfer to *PSI* can be considered as additional competitive pathway of de-excitation of *PSII*. Chlorophyll *a* fluorescence emission presents a small (2-5 %) part of absorbed energy and depends on the type of chloroplast, physiological state of photosynthetic organism, stress conditions, intensity and wavelength of excitation radiation.

Electron transfer along electron-transport chain is accompanied with decrease (*quenching*) of the chlorophyll fluorescence. The quenching which is related to the oxidation of acceptor is defined as *photochemical quenching*. This process is characterized by coefficient of photochemical quenching *qP*. Simultaneously there are other mechanisms of quenching of nonchemical nature or *nonphotochemical quenching*, which are characterized by coefficient of nonphotochemical quenching *qN*. It is necessary to distinguish energy dependent quenching which is associated with proton-induced gradient across thylakoid membrane, and quenching which can be significant under high intensity irradiation; this type of quenching provokes photoinhibition. In such a way, fluorescence is a complementary process in relation to photochemical and thermal processes: the more energy on photochemical reactions or heat is wasted the less fluorescence is yield.

The temporal behaviour of the fluorescence intensity has a complex character. The fluorescence kinetics of dark-adapted green plant sample (induction of fluorescence, Kautsky effect) reflects the sum total of processes which are linked with photosynthesis activity of a plant object.

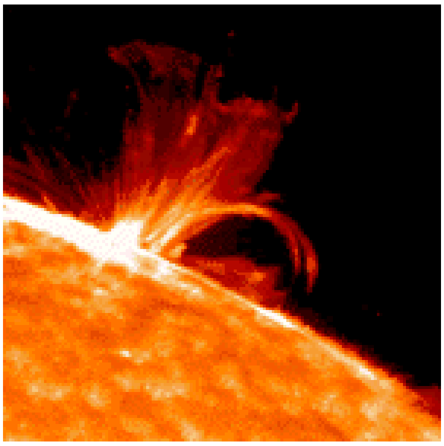
The control of fluorescence emission at two wavelengths is realised at 690 and 735 nm which correspond the maxima of fluorescence emission of chlorophyll. The measurements of vitality index $Rfd = f_d / f_s$ ($Rfd^{/}$ at 735 nm and $Rfd^{//}$ at 690 nm), and stress adaptation index $A_p = 1 - [Rfd(735)+1]/[Rfd(690)+1]$ provide useful information about healthy status of plant objects under stress conditions.

It is possible to study the effects various stress such as high photosynthetic and ultraviolet radiation, extreme temperature, water deficit, agrochemical treatment, character of soil processing on agronomic plants on plant status.

Photoperiodism

The response of the functional or behavioral response of an organism or population of organisms to changes of duration in daily, seasonal, or early cycles of solar activity is called *photoperiodism* (or *periodicity*).

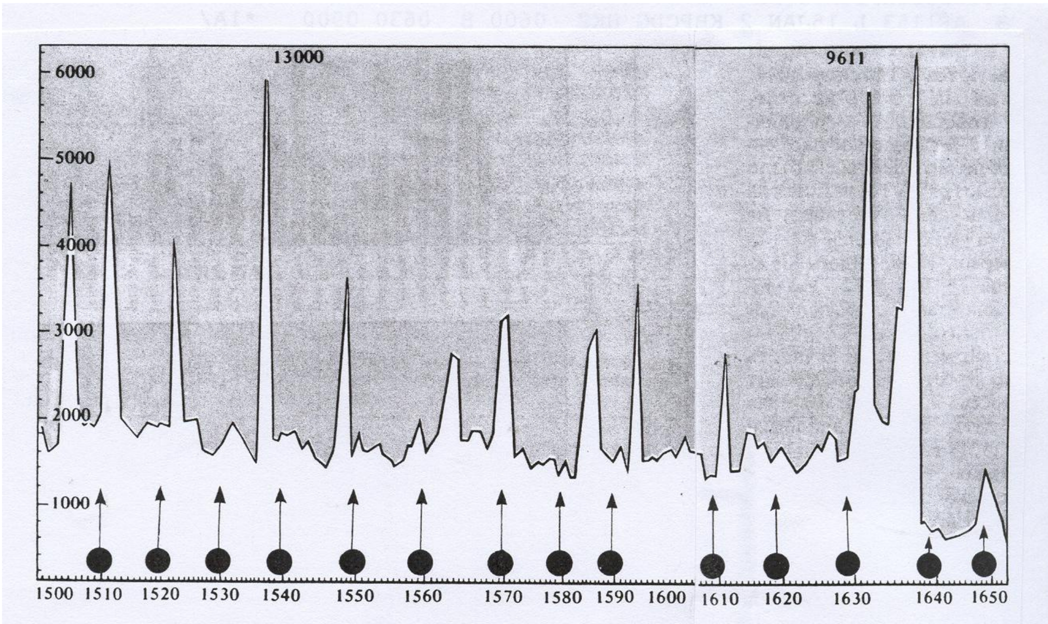
Professor Aleksandr Chizhevsky (1897-1964) investigated the correlation between sunspots and human activity − battles, wars, revolutions, splashes of human aggression, social explosions. According to Chizhevsky the French revolutions of 1789, 1830 and 1848, the commune of 1870, the two Russian revolutions of 1905 and 1917, the second world was related with maxima of solar activity. More latter historical events such as the invasion to Czechoslovakia in 1968 and Afghanistan in 1979, war conflict in Falkland in 1982, perestroika and declaration of the independence of former Soviet republics in 1990-1991 confirmed the theory of Chizhevsky.



Solar Spot (from blog.deadlycomputer.com)

Alexandr Chizhevsky (1897-1964)

Chizhevsky reported a coincidence of maxima of solar activity with disturbances of human health, epidemics of cholera, influence, diphtheria, plague, meningitis, typhoid, malaria.



Mortality in Ausburg from 1501 till 1650 that was provoked by epidemics mainly by plague. The arrows correspond to the maxima of solar activity (from A. Chizhevsky, The Terrestrial Echo of Solar Storms, 1976)

Photosensitization

Oscar Raab investigated in 1900 effect of light and chemical substance − acridine on viability of paramecia. He found, that light alone didn't induce any effect on paramecia; acridine alone didn't provide any effect on the cells also; but simultaneous action of both factors − light and acridine led to the inactivation of paramecia.

The process of sensitization of living organism to simultaneous action of light and certain chemicals that leads to the disturbance of its viability is called *photosensitization*. This process is accompanied with absorption of light energy by molecules that have chromophores and transfer this energy to other molecules that are not able to absorb light independently.

This phenomenon is spread in nature widely. Some herbivorous animals eat plants that contain some chemicals such as species of *Guttiferae* (*Hypericum perforatum*, *H. crispum*, *H. pulchrum*, *H. leucoptycodes*, *H. maculatum*); *Fagopyrum* (*F. esculentum* або *Poligonum fagopyrum*); genus *Tribolus* (*T. terrestris* and *T. ubis*, family *Zygophyllaceae*); some species *Lippia* (*L. rhenanni* and *L. pretoriensis*, family *Verbenaceae*); grass *Pannicum* (*P. laevifolium* and *P.coloratum*, family *Graeminae*). In Ukraine such plants as *Trifolium L.* and *Sysimbrium altissimum L.* exhibit photosensitization.

Plant compounds or pigments are absorbed by the digestive system and provoke a direct effect on non-pigmented parts of skin such as near eyes, mouth, ears and hoofs when they are exposed to sun light. The final result is the necrosis, itch, scab formation, and infection of organism. The animal can die in 8-10 hours.

The leg of animal that is suffered with photosensitization (from www.northwestweeds.nsw.gov.au)

The mechanisms of photosensitization can be explained on the basis of the interaction of the quantum of light with the molecule of photosensitizer that can be described by the following pathways:

1) Light absorption my molecule of photosensitizer and its excitation

$$S_o \ + \ hv = S\square_1; \qquad (5.1)$$

2) Intersystem crossing

$$S_1 \rightarrow T_1 ; \qquad (5.2)$$

Besides, such processes are possible as

3) Fluorescence

$$S_1 \rightarrow S_0 + hv; \qquad (5.3)$$

4) Non-radiative transition

$$S_1 \rightarrow S_o . \qquad (5.4)$$

There are two main mechanisms of photosensitized reactions. The first type (mechanism I) is characterized by the energy transfer from the sensitizer molecule which is excited in the triplet state to the substrate molecule

$$T_1 + M \rightarrow S^{\cdot -} + M^{\cdot +} . \qquad (5.5)$$

The formation of the free radical-species which interact with oxygen is the result of this process

$$M^{\cdot +} + {}^3O_2 \rightarrow S_o + {}^1O_2 . \qquad (5.6)$$

The second type (mechanism II) provides the energy transfer from the triplet-excited molecule of sensitizer to molecule of oxygen

$$T_1 + {}^3O_2 \rightarrow S_0 + {}^1O_2 . \qquad (5.7)$$

The next pathway is the oxidation of the substrate molecule

$$^{1}O_2 + M \rightarrow M(O_2)\,. \qquad (5.8)$$

Either free radicals or singlet oxygen are strong reactive substances which provoke the disturbance of functions of living organism.

Photomovement

The term *photomovement* in a wide meaning defines any movement or its alteration induced by light. Photomovement is a result of *photoregulation of movement* – the whole complex of elementary processes caused by light stimulus such as: photoreception, primary reactions of photoreceptor pigments, sensory transduction of light stimulus into physiological signal that governs the activity of motor apparatus and realises the photoorientation of organism.

Nowadays the problem of photomovement and photoregulation of movement of microorganisms is being investigated rather extensively. This may be explained by the importance of these phenomena, which are connected with fundamental processes of viability such as photosynthesis, photoreception, energy transformation, membrane-coupled and membrane-mediated phenomena.

The investigations of photomovement and its photoregulation are directly related to the elucidation of general principles of intracellular processes of metabolism, as wells ontogenesis, embriogenesis, morphogenesis. These investigations may play a fundamental role for ecology and biocenology, because light is an important factor for spatial and temporal distribution of microorganisms, which has an independent function and at the same time informs us about the complexity of related environmental factors related to it (i.e., temperature, pH, biogenous compounds and oxygen content, the presence of other microorganisms, etc.

Finally, the investigation on photomovement regularity could be of practical use in research fields such as biomonitoring of environment where microorganisms are used as test-objects, and parameters of photomovement – as test-functions.

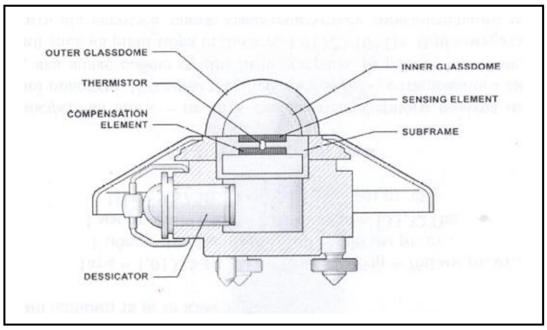
Measurement of Solar Radiation

Radiometer is a device that is used for measuring the radiant flux or power in electromagnetic radiation. An instrument that is used to measure the heating power of radiation is called *actinometer*.

All radiometers can be classified as *thermal detectors* which are based on absorbing radiation and converting that to a thermal energy which can be measured, and *quantum detectors*, that produce as a result of the absorption of energy of photon a photovoltage or photocurrent. The main characteristics of radiometer are: spectral range, spectral sensitivity, field of view, and directional response.

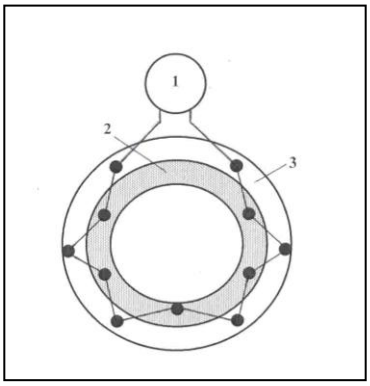
Pyranometer is a radiometer for measuring the solar irradiance (radiation flux density, W/m^2) on a plane surface, which results from direct solar radiation and from the diffuse radiation incident from the hemisphere above.

Pyranometer CM 11
From: http://www.rg-messtechnik.de/index.cfm?cftoken=18662630&cfid=1192366&&n002=product&product=2902&n00



Construction of Kipp & Zonen pyranometer CM11
From:
http://www.kippzonen.com/download/kipp_manual_cm14_1547.pdf

Pyranometer contains a thermopile sensor which absorbs solar radiation from 300 to 50000 nm due to black coating; this sensor is maintained into a glass dome that limits the spectral response from 300 to 2800 nm and shields the thermopile sensor from convection. Solar radiation that is absorbed by a thermopile sensor is converted to heat and then − to a voltage output signal that is proportional to this radiation.



Thermopile sensor of radiometer: 1 – voltage signal measurement; 2 – cold junctions; 3 – hot junctions of thermopile.

Prof. Kyoichi OTSUKI near devices for measuring solar radiation in Sasaguri region, Japan

The sensing element of the pyranometer CM-11 is a black painted ceramic Al_2O_3 disk; it contains 100 thermocouples forming a thermopile that are imprinted on it. Cold junctions of thermopile are located at white sensing part that is in contact with the pyranometer body, while hot junctions are located at black sensing part that is in contact with near the centre. When the sensor is exposed to solar radiation, a temperature difference is created between the black and white parts; this difference is proportional to the radiation intensity.

A *net radiometer* is a type of actinometer used to measure net radiation at the Earth surface particularly incoming shortwave radiation from the Sun minus upwelling longwave radiation from the Earth surface. It consists of shortwave and longwave sensors correspondingly.

A Net Radiometer

Quantum Sensor

Quantum Sensor is a device, such as a photoelectric cell, that receives and responds to a light stimulus and produces an analog voltage response proportional to the intensity of this stimulus.

Quantum sensors of series LI-COR LI-190 measure photosynthetically active radiation (PAR) in the 0.4 to 0.7 micron waveband within plant canopies, forests, at remote environmental monitoring. The radiation in this range can be measured in energy units (watts m^{-2}) or as Photosynthetic Photon Flux Density (PPFD), which has units of quanta (photons) per unit time per unit surface area. The units most commonly used are micromoles of quanta per second per square meter (mmol s^{-1} m^{-2}).

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6. RECIPITATION

Definitions

Any form of water, such as rain, drizzle, snow, snow grains, snow pellets, diamond dust, hail, and ice pellets, that falls to the earth's surface is called *precipitation*.

Rainfall is the quantity of water falling in a given area within a given period of time; it is estimated as the depth of water that has fallen into a rain gauge.

Precipitation is a result of saturation of atmospheric vapour; the saturated water vapour condenses on small hygroscopic nuclei within the aerosols (condensation nuclei) and process of precipitation takes place. This process depends on the atmosphere temperature: the drops of water are formed at the temperature $T_a < 273.2$ K and particles of ice – at the temperature $T_a < 233$ K.

The transfer from fog (cloud) to rain is determined by the velocity of raindrops movement, that is related to its size. Cloud droplets have spherical shape; its size is less than 0.1 mm; raindrops have oblate form and range of size from 0.1 mm to 9 mm.

Parameters of Precipitation

Total amount of precipitation is estimated by the vertical depth (in millimetres) of water which reaches the ground to which it could cover a horizontal projection of the Earth's surface.

Rate of precipitation (intensity) is expressed in millimetres per hour and is classified as:

Very light rain – when the precipitation rate is less than 0.25 mm/hour;
Light rain – when the precipitation rate is between 0.25 mm/hour – 1.0 mm/hour;
Moderate rain – when the precipitation rate is between 1.0 mm/hour – 4.0 mm/hour;
Heavy rain – when the precipitation rate is between 4.0 mm/hour – 16.0 mm/hour;
Very heavy rain – when the precipitation rate is between 16.0 mm/hour – 50 mm/hour;
Extreme rain – when the precipitation rate is > 50.0 mm/hour.

Duration of precipitation – parameter that characterizes as long the precipitation takes place. High intensity precipitation is likely to be of short duration and low intensity one can have a long duration.

Night Rain on Karasaki Pine by Katsushika Hokusai (1760 – 1849). At: http://www.art.com/asp/search/productsearch-asp/_/results.htm?search_string=PINE&pg=9

Fedor Vasiliev (1857-1873)
After the Rain
At:
http://bibliotekar.ru/kVasilievFedor/6.htm

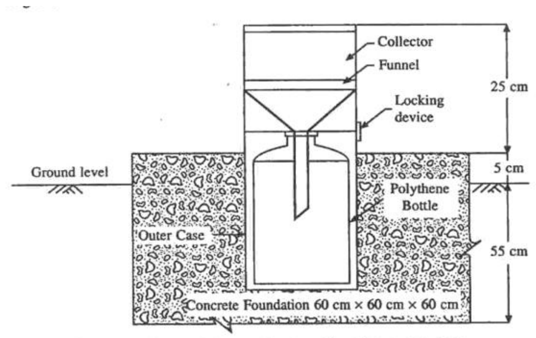
Measurement of Precipitation

Precipitation is estimated due to the *rain gauges* – the instruments that gather and measure the amount of liquid precipitation over a certain period of time. For example, precipitation can be measured in millimetres or inches per 24-hour period. The procedure of measurements means that water isn't absorbed by the ground and doesn't flow downhill.

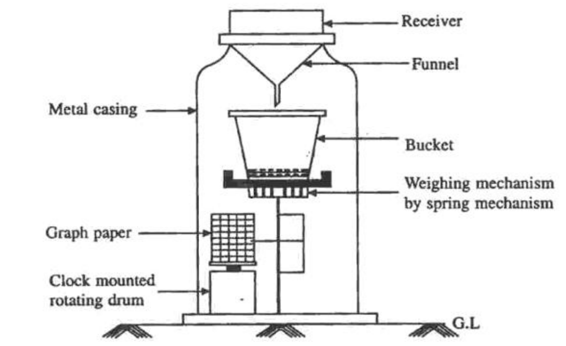
There are several types of rain gauges:

Storage Rain Gauge consists of the circular collector with an open area of 100 or 200 cm^2. The rain enters through this area and funnel to collector. The top of this device is placed at the height of 30 cm above ground level. All the construction is settled in concrete foundation.

Weighing Bucket Gauge can be used for recording rainfall. Water is collected in a receiver bucket that is supplied with spring mechanism. The lever arm of this mechanism is connected with a pen that touches a clock mounted drum with a graph paper. The weight of this bucket is increased during the rain and the position of the pen is changed. The process of recording continues either 24 hours or 7 days.

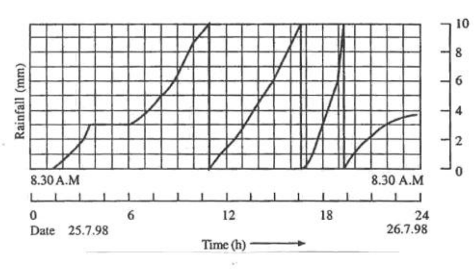


A Standard Gauge
After Patra K.C. (2000) Hydrology and Water Resources Engineering Narosa.

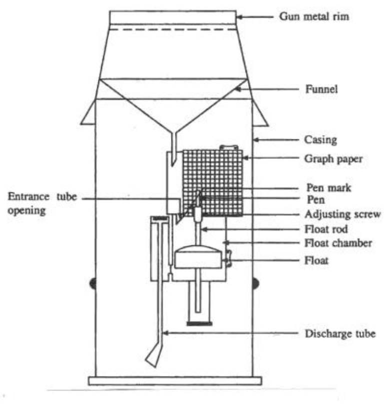


A Weighing Bucket Rain Gauge.
After Patra K.C. (2000) Hydrology and Water Resources Engineering Narosa.

Syphon (Float) Automatic Rain Gauge. Rain enters through the tube opening into a float chamber. When rainfall is increased, the float rises and the pen mounted on it touches a graph paper of the clock mounted drum.



Rainfall Mass Curve from a Syphon Rain Gauge. After K.C. Patra, Hydrology and Water Resources Engineering



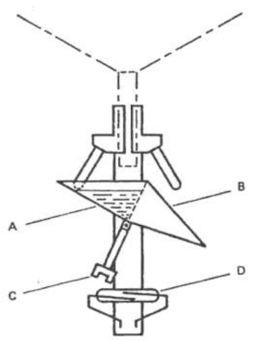
A Syphon (Float) Automatic Rain Gauge. After K.C. Patra, Hydrology and Water Resources Engineering

If the pen reaches the top of the graph the float reaches the top of the chamber which is become free from the water due to syphonic action. In this situation the pen returns to zero position. One syphonic action means 10 mm of rainfall; the time that is taken to collect the depth of rain is indicated on the horizontal axis of the graph.

Tipping bucket gauge consists of two-compartmental buckets, triangle in section. One of them is always is beneath the drain tube from the collecting cone. When the rain water fills up one of the bucket, the centre of gravity is displaced, it over-balanced and the water leaves the bucket; this causes the second bucket to take position below the drain tube and the process begins again. Movement of the buckets is matched by a small magnet that closes a contact in electric circuit; the number of tips and closures corresponds to the intensity of rainfall.

A Tipping Rain Gauge RT-5 (Ikeda Keiki, Japan) in Kahoku Experimental Watershed, Japan

Dr. Takanori SHIMIZU, Kyushu Research Center, Japan



Principle of action of Tipping Bucket Rain Gauge.

Raine gauge RT-5 Ikeda Keiki, Japan

Collector for Chemical Analysis is used for analysis of pH, ions, ammonium, aluminium, chloride, and stable isotope samples. The principal feature of such a collector is prevention of water evaporation which is inhibited due to the application of narrow tube between the funnel and plastic can.

Left: Collector for chemical analysis of precipitation. *Right*: Preparation of precipitation sample by post-graduated students Ishita SACHIE and Yuka MAEDA, Toyama University, Japan

Remote Sensing Precipitation provides determination of type, range, location, motion and intensity of precipitation due to the application of *radar*. The term *RADAR* means the acronym of the phrase that explains the principle of action of this device: *Ra*dio *D*etection *A*nd *R*anging.

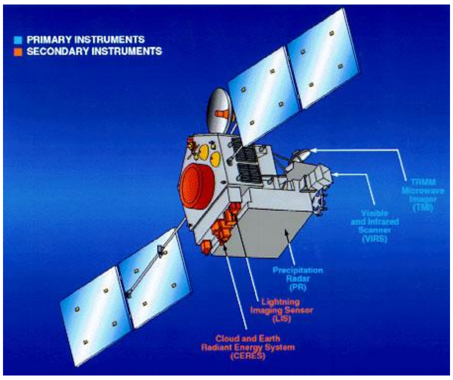
Modern radar systems include *Doppler radars* that capable to estimate velocity of movement of rain droplets. This type of radar is based on the *Doppler effect* – the change in frequency ν (wavelength λ) of a wave for an observer moving relative to the source of the waves. When either the source or the receiver of a propagating wave moves, there is usually a change in frequency called the *Doppler shift* $\Delta\nu$ which depends on the velocoity and direction of movement of object.

One of modifications of weather radar is *polarimetric radar* that transmit radio wave pulses that have both horizontal and vertical orientations. Such a radar makes it possible to determine the horizontal and vertical dimensions of cloud and precipitation particles.

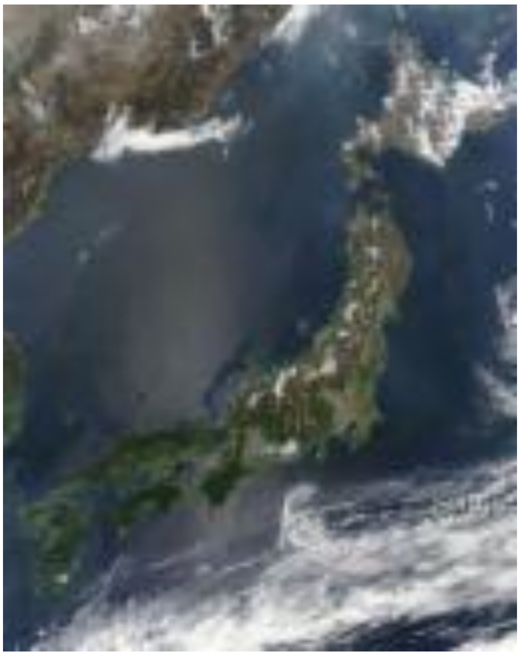
Satellites are used for precipitation analysis and forecasting. Some of them are geostationary (geosynchronous) satellites which have circular orbit over the equator (GOES-8, GOES-10, GMS-5, Metsat-6, and Metsat-7); another class is presented by low-orbital satellites such as TRMM, NOAA-15, -16, -17, DMSP F13, F14, F15.

It should be mentioned the *Tropical Rainfall Measuring Mission* (*TRMM*) satellite, a joint project between the United States (under the leadership of NASA's Goddard Space Flight Center) and Japan (under the leadership of the National Space Development Agency), which was launched from Tanegashima, Japan, in 1997 to monitor rain over the tropics. It placed in low earth orbit the precipitation radar (PR) to be flown in space, along with a passive microwave imager (TMI), a visible-infrared radiometer (VIRS), a lightning sensor and a cloud sensor.

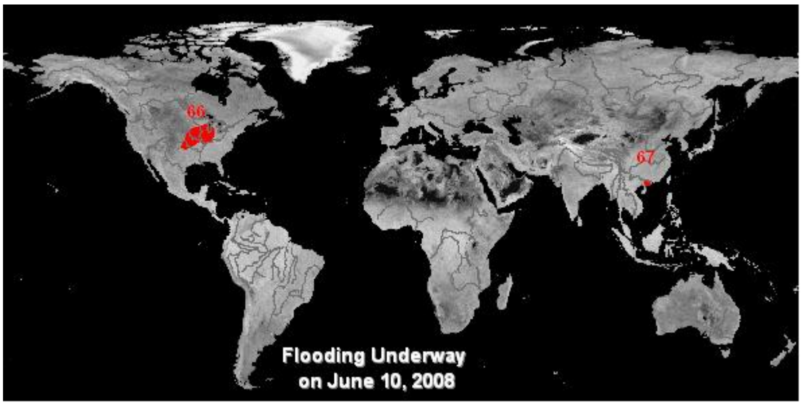
This satellite is capable to provide the analysis of the inter-annual variability of global rainfall and to obtain radar images of rain from space.



Tropical Rainfall Measuring Mission (TRMM) US-Japan satellite
After: mynasadata.larc.nasa.gov



The satellite systems are capable to study tropical and subtropical rainfall, to predict flooding and to help scientists to understand global climate changes.



World Map of Flooding
http://www.dartmouth.edu/%7Efloods/

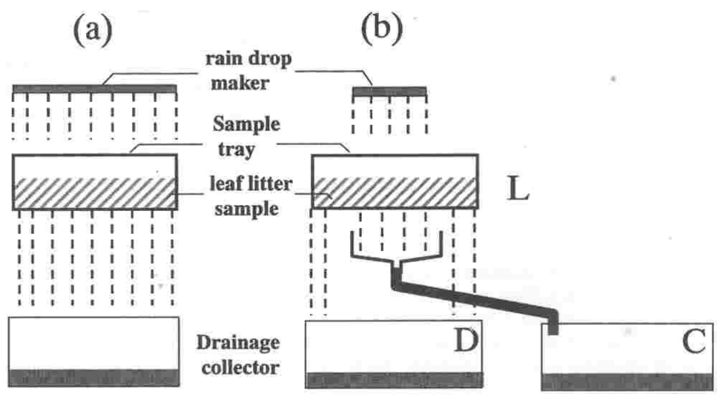
Fog Water Measurement. A cloud that contacts with the ground is called *fog*. The density of fog is about 0.05 kg/m^3; diameter of droplets is 1–40 µm. Fogs are important sources of moisture and nutrients required for forest ecosystems. Investigation of main properties of fogs gives useful information about acid deposition, water balance and canopy-fog interaction.

The fog water is collected usually by Passive String Collector. It constitutes the cylinder 21×45 cm with total collection surface 945 cm^2. The fog droplets are collected by the 460 vertical Teflon strings arranged cylindrically, combine to larger drops that run down the strings and are accumulated for analysis.

Passive String Collectors in Kahoku Experimental Watershed, Japan

Practical Applications

The interception storage capacity of a litter layer, composed of dead leaves, twigs and other fragmented organic materials covering the soil, was studied by using an artificial rainfall simulator [Sato et al., 2004].



Experimental set-up for measurement of litter interception storage capacity. (a) Standard set-up. (b) Extra set=up to investigate the litter flow mechanisms.
C: Drainage from the centre. D: Drainage outside the centre.
After Sato et al., 2004.

The litter layer plays an important role in preventing soil erosion by absorbing the impact energy of raindrops; removal of this layer during forest fire or other phenomena, decreases the protection of the soil surface. In addition, the litter layer helps limit soil moisture loss from evaporation and reduces the amplitude of soil temperature by insulating the surface.

Application of artificial rainfall simulator made it possible to model the rainfall conditions such as intensity and duration of rainfall and to study the moisture dynamics of a litter layer. Two contrasting litter types were used in this investigation: a needle-leaf type, represented by *Cryptomeria japonica* leaves, and a broad-leaf type, represented by *Licthocarpus edulis* leaves.

It was shown that the maximum water storage capacity of each litter layer was proportional to the litter mass (kg/m^2) regardless of layer thichness; the litter interception storage capacity increased with rainfall intensity in the range of realistic rainfall conditions (under 50 mm/h); the broad-leaf litter of *L. edulis* intercepted more rainwater than the needle-leaf litter of *C. japonica*; the rainwater moved laterally in the litter layer of *L. edulis*whereas it moved directly down in the litter layer of *C. japonica*. In such a way, not only the litter mass but also the rainfall conditions and leaf shape are important in evaluation the moisture dynamics of litter layer.

Acid Rains

Acid precipitation arises due to natural (volcanic gases, forest fires, ocean surface evaporation) and industrial (automobile exhausts, burning of industrial fuels) discharges of sulphur and nitrogen oxides in atmosphere, where they are transformed into sulphate and nitrate particles that are mixed with water moisture, form sulphuric and nitric acids and return at the Earth's surface due to the sedimentation or precipitation.

The process of formation of acid rain is accompanied with the following chemical reactions:

Wet deposition of acids occurs when falling rain droplets collide with aerosol particles in atmosphere or when water droplets in clouds collide with aerosol particles. As result the

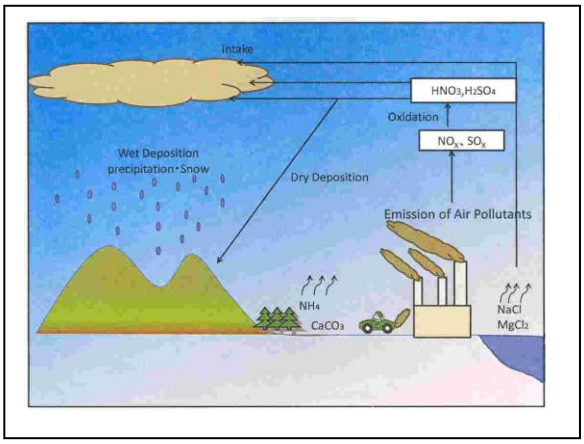
$$SO_2 + OH \rightarrow HSO_3; \qquad (6.1)$$

$$HSO_3 + O_2 \rightarrow HO_2 + SO_3; \qquad (6.2)$$

$$SO_3 + H_2O \rightarrow H_2SO_4; \qquad (6.3)$$

$$NO_2 + OH \rightarrow HNO_3. \qquad (6.4)$$

The main result of these reactions is production of sulphuric and nitric acids.



Process of formation of acid rain.
Courtesy of Dr. Yoshitoshi UEHARA

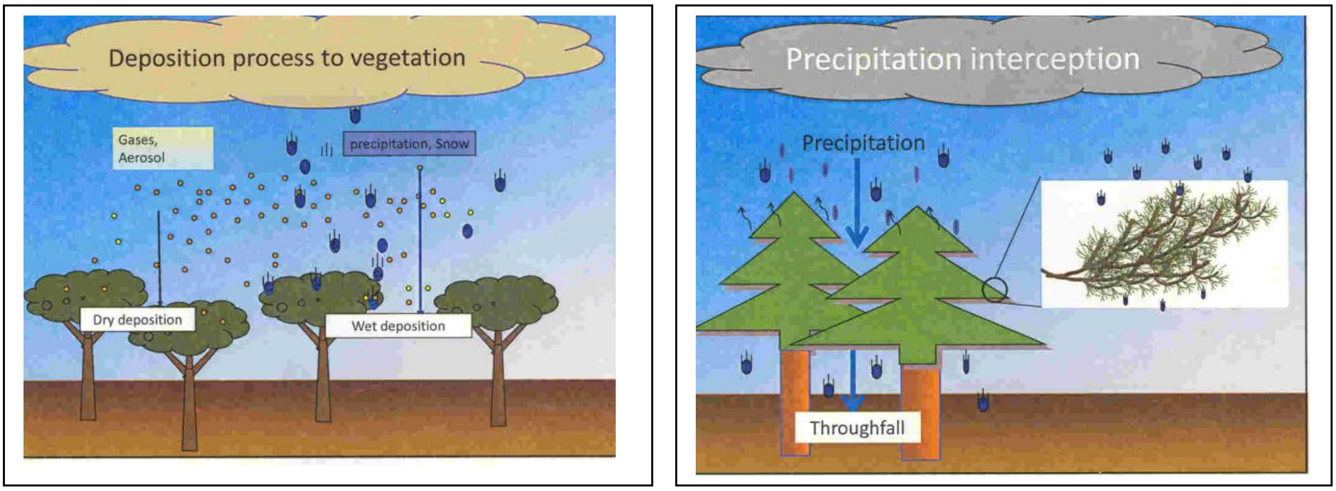
Wet deposition of acids takes place during the removal of acids from the atmosphere by precipitation.

Dry deposition can play role of carrier of acids in the absence of precipitation. The principal causes of dry deposition are gravitational sedimentation, interception, interaction of small particles with bigger obstacles, collision of particles due to diffusion and turbulence.

Interception

The process of flowing rain droplets too close to the leaves or plant branches, limbs and stems that the certain part of precipitation is retained and doesn't reach the ground is called *interception*. The intercepted part of precipitation evaporates back to the atmosphere.

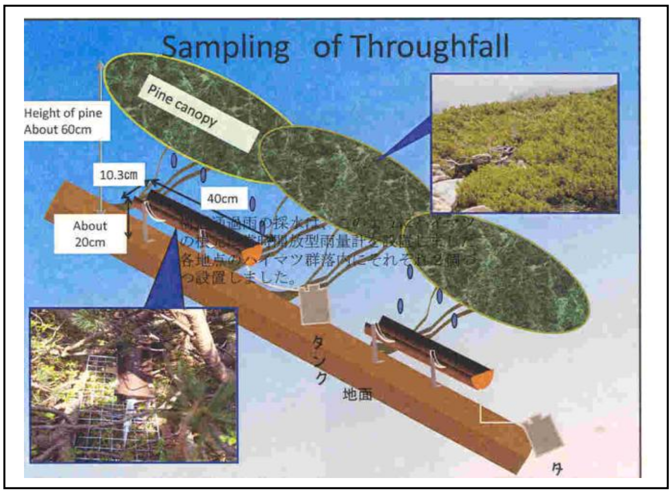
Those part of rainfall that is not intercepted is called *throughfall*.



Deposition processes and precipitation interception.
Courtesy of Dr. Yoshitoshi UEHARA

The process of canopy interception depends on the type of foliage (coniferous trees have greater interception than deciduous trees), growth form (trees, grasses, forbs), density of vegetation, plant structure, meteorological factors (intensity, duration and frequency of precipitation, wind, solar radiation).

Control of interception is important from the point of view of studying the processes of acid rain formation and its effects on forest ecosystems.



Rainfall interception by canopy of Dwarf stone pine in Toteyama alpine and sampling of throughfall.
Courtesy of
Dr. Yoshitoshi Uehara

Wet Deposition Monitoring

The first approach in monitoring the acidity of acid rain is to measure the pH and conductivity of collected rain samples.

pH-metry

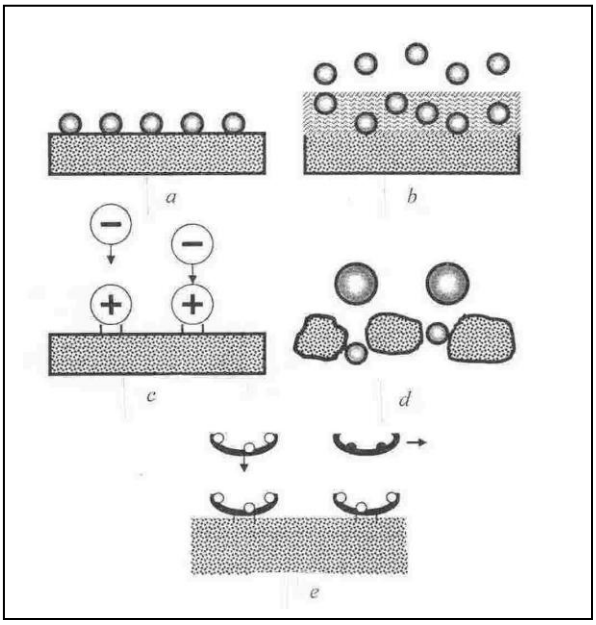
Principle of action of pH-meter is based on estimation of the concentration of hydrogen ions that determines the level of acidity (pH level). The H+ is produced by the reaction of acids dissolved in the rainwater with the water itself. A typical pH-meter consists of special glass electrode connected with an electronic meter that provides the measurement of pH level. The scale of acidity (alkalinity) extends from 0 (maximum acidity) through 7 (neutral point) to 14 (maximum alkalinity). If rain has pH 0-5 it is considered to be acid rain. Clean rain has pH 5.6.

Conductivity

The electrical conductance of a solution is a physical value that estimates the ability of a solution to conduct a current. This current is produced by movement ions through solution. So, electrical conductance is proportional to the ion concentration and therefore to pH level of solution. The units of electrical conductivity are decisiemens per meter (dS/m) or micro-siemens per centimeter (μS/cm). The scale of electrical conductance begins with absolute pure water (0.055 μS/cm)and extends through distilled water (0.5 μS/cm) and demineralised water (5 μS/cm) to water streams (10-500 μS/cm) and concentrated acids and bases (10^5 μS/cm).

Ion-Exchange Chromatography

Chromatography is (from Greek χρώμα: *chroma*, colour and γραφειν: "grafein" to write) is method of the separation of the mixtures and the identification of their components which is based on the differences in partitioning behavior of analytes between a mobile phase and a stationary phase. Mechanisms of interaction of the components of mixture with the stationary phase can be various, based on adsorption or solubility, charge interaction, van der Waals' forces, size separation, different affinity.



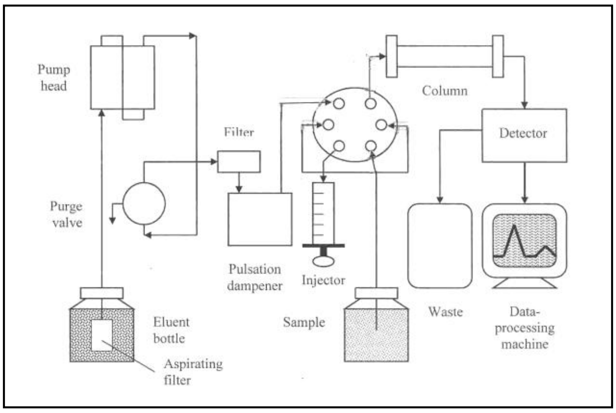
Mechanisms of interaction of the components of mixture with the stationary phase: *a* –adsorption; *b* – solubility; *c* – coulombic (ionic) interaction; *d* – separation of small molecules from large molecules; *e* – affinity of certain molecules with mixture of other molecules.

Ion-exchange chromatography (or *ion chromatography*) is a process that allows the separation of ions and polar molecules based on the charge properties of the molecules and their coulombic (ionic) interactions. The solution to be injected is usually called a *sample*, and the individually separated components are called *analytes*.

The stationary phase surface displays ionic functional groups that interact with analyte ions of opposite charge. Ion chromatography is the only technique that can realize quantitative analysis of anions at the ppb level.

The 761 Compact IC System consists of injection valve for individual injections; high-pressure pump with a flow range from 0.2 … 2.5 mL/min and a maximum pressure of 25 MPa; pulsation dampener for protection the column against damage even with low-level pressure variations; column chamber with the perfect insulation of the housing with thermally stable conditions and shielding the system against electromagnetic interference; column; conductivity detector with outstanding temperature stability; eluent and sample bottles.

A sample is introduced into a sample loop of known volume. A buffered aqueous solution known as the mobile phase carries the sample from the loop onto a column that contains some form of stationary phase material.



Connecting diagram for 761 Compact IC without suppressor

761 Compact IC in Toyama University

A column Hamilton PRP-X100 on styrene/divinylbenzene copolymer basis is used for the separation of chloride, nitrate and sulphate without chemical suppression.

A column Hamilton PRP-X100

Dr. Yoshitoshi UEHARA at ion-exchange chromatograph at Toyama University

Usually the mobile phase contains ions that produce a background conductivity that makes it difficult to measure proper conductivity of the analyte. The problem is resolved due to the application of eluent suppressor which consists of an ion-exchange column. During cation analysis the mobile phase is often *HCl* or HNO_3; the suppressor column retains or removes ions Cl^- or NO_3^-. In anion analysis the mobile phase is often *NaOH* or $NaHCO_3$; the suppressor supplies H^+ to neutralize the anion and retain or remove the Na^+. Such a suppressor improves sensitivity and consistency of the system.

Application of Isotope Techniques

Rainfall interception by canopy of Dwarf stone pine in Tateyama alpine zone was investigated [Yoshitoshi Uehara, private communication]. The main pollutants are emitted from the terrestrial surface: NH_4 and $CaCO_3$ from the vegetation; NO_x and SO_x from industrial sources (the process of oxidation of these compounds leads to formation of HNO_3 and H_2SO_4); *NaCl* and $MgCl_2$ are emitted from sea reservoirs. These pollutants return to terrestrial surface as wet deposition (precipitation, snow) and as dry deposition (gases, aerosols). Rainfall interacts with vegetation canopy; part of it passes through canopy as throughfall. The samples of water before interaction and after interaction of precipitation with vegetation were collected by Bulk type Rain Collector into 10 L tank. Besides, 0.2 mm fall measure type gauge was used to measure the time and precipitation in which rain come down. The fog water was collected by Passive String Collector. The ion composition of the samples (cations Na^+, Mg^{2+}, Ca^{2+}, NH_4^+ and anions Cl^-, NO_3^-, SO_4^{2-}) were analysed with ion-exchange chromatograph 761 COMPACT.

The ionic composition of precipitation and throughfall on southern and northern side slopes of Jodo (2850 m) was studied. It was suggested that such environmental factors as a wind and fog affect considerably on the throughfall. The flux budget of nss-SO_4^{2+}, NH_4-N, NO_3-N and nss-Mg^{2+} was analysed quantitatively.

ISOTOPE IN PRECIPITATION

General Characteristics of Isotopes

The nuclei of atoms of a particular chemical element that contain the same number of protons (that corresponds to the same atomic number and position in the periodic table) but different numbers of neutrons are called *isotopes*. Therefore, isotopes have different atomic masses and physical properties. Each chemical element has one or more isotopes.

The term “isotope” is derived from Greek *ίσος* (iso-, "equal", "same") + *τόπος* ("place") because of the same position in the periodic table that is occupied by the different isotopes of a chemical element.

Stable isotopes mean those isotopes of an element which are stable and do not undergo radioactive decay over time.

Water Stable Isotopes

Water (H_2O) has two elements: hydrogen H and oxygen O. Hydrogen, and oxygen have the following stable isotopes:

^{1}H: 99.9844%;
^{2}D: 0.0156%;
^{16}O: 99.763%;
^{17}O: 0.0375%;
^{18}O: 0.1995%.

It is clear that almost all water atoms consist of the lightest atoms ^{1}H and ^{16}O. Practically, it is possible to find water with one of the three atoms replaced by a heavier nuclide, for instance, ^{16}O replaced by ^{18}O and ^{1}H replaced by ^{2}D.

Isotopic Fractionation

Application of modern analytical equipment demonstyrates that various isotopes of any element behave differently in both physical processes (heavier isotopic molecules have a lower mobility and diffusion velocity, higher binding energy) and chemical reactions (because the atoms of different isotopes are of different sizes and different atomic weights). The phenomenon that this isotopic differences in physical and chemical behaviour exists is called *isotopic fractionation*.

Stable isotope abundances are expressed as the ratio of the two most abundant isotopes in the sample compared to the same ratio in an international standard, using the “delta” (δ) notation. Because the differences in ratios between the sample and standard are very small, they are expressed as parts per thousand or ”per mil” (‰) deviation from the standard. δ notation can be expressed as

$$\delta_{sample} = [(R_{sample} - R_{standard})/(R_{standard})] \times 1000, \qquad (6.5)$$

where R_{sample} is the ratio of $^{18}O/^{16}O$ or $^{2}H/^{1}H$ in the sample and $R_{standard}$ is the ratio of the international standard for oxygen and hydrogen.

The standard is defined as 0‰. The Table 6.1 shows the international standards and their absolute isotope ratios for the several environmental isotopes. Some elements, such as oxygen and hydrogen, have more than one international standard.

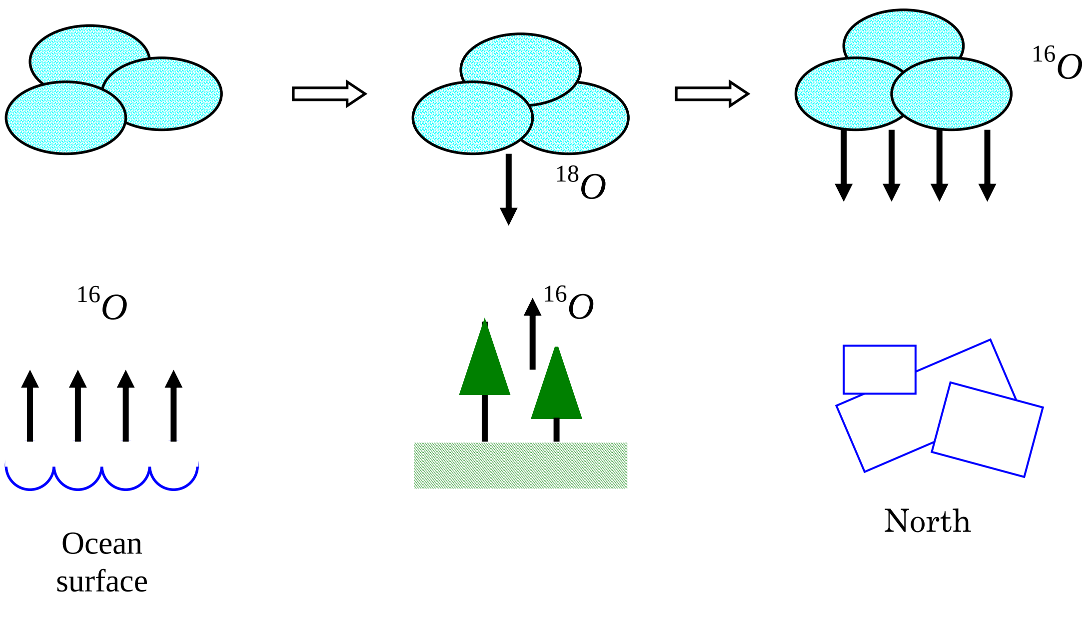
6.1. The international standards and their absolute isotope ratios for the several environmental isotopes

Element	**δ value**	**Ratio Measured (R)**	**International Standards**	**R, International Standards**
Hydrogen	δD	$^{2}H/^{1}H$	Vienna Standard Mean Ocean Water (VSMOW)	0.00015575
		$^{2}H/^{1}H$	Standard Light Antarctic Precipitation (SLAP)	0.000089089
Oxygen	$\delta^{18}O$	$^{18}O/^{16}O$	Vienna Standard Mean Ocean Water (VSMOW)	0.0020052
		$^{18}O/^{16}O$	Vienna Pee Dee Belemnite (VPDB)	0.0020672
		$^{18}O/^{16}O$	Standard Light Antarctic Precipitation (SLAP)	0.0018939

Seawater has a δ^{18}O value of 0‰. In such a way, water with negative δ^{18}O or $\delta^{2}H$ is said to be *depleted* relative to seawater, while those with positive δ values is said to be *enriched*.

Stable Isotopes in Precipitation Processes

The changes of the isotope ratios during the water cycle are related mainly to the processes of evaporation and condensation. Global weather, regional topography and moisture distribution affect the isotope ratios. The nuclei of atoms are responsible for its physical properties. The lighter molecule of water has the higher vapour pressure; thus water evaporates from warm ocean surface and its vapour is enriched in lighter isotope ^{16}O. Plants supply also atmosphere with lighter isotope ^{16}O. These moist air mass moves toward the North where it is cooled and provide a precipitation enriched in heavier isotope ^{18}O while the remaining air consists of strongly ^{16}O isotope.



Thus, application of isotope techniques to ecohydrology makes it possible to determine the origins and ages of different water bodies, estimate the level of mixing, determine the location and proportion of water recharge; and can indicate the velocity of ground water flow.

Isotope Ratio Mass Spectrometry

Isotope ratio mass spectrometry (IRMS) is a special field of mass spectrometry, which provides the precise measuring the mixtures of stable isotopes and estimating relative abundance of these isotopes.

The principle of action of isotope ratio mass spectrometer is based on precise analysis of the stable isotopic compositions of $\delta^{18}O$ and δD; the sample is converted to a gas and the pressures of sample and reference gases are adjusted due to compressing or expanding the bellows until both pressures are the same. Dual inlet system of gas isotope ratio spectrometer is equipped with changeover valves for rapid switching between sample and reference gas. These valves are prepared from teflon or gold to eliminate leakage of the gases and contamination of one gas by the other.

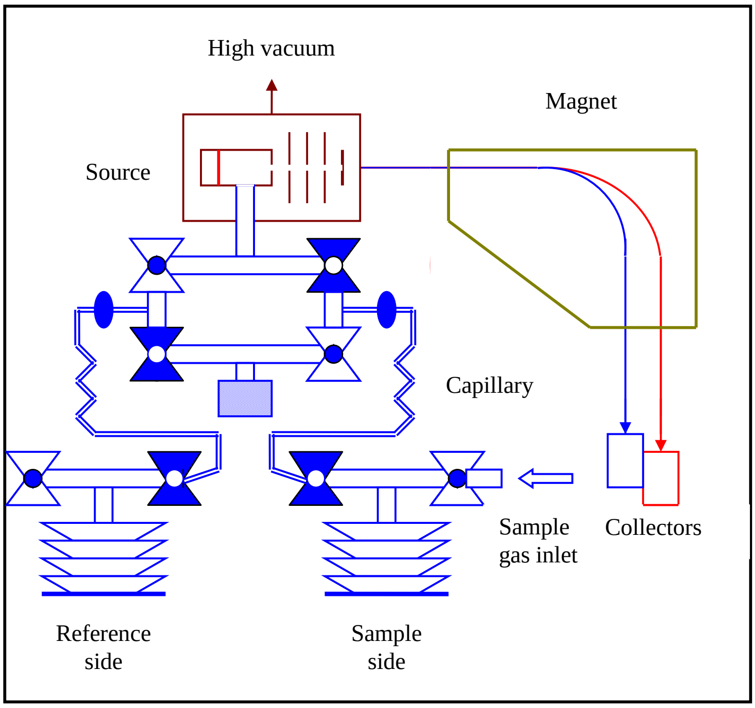
Then each gas passes through a capillary column (about 1 m of length) which is supplied with a crimp that is located at the end of mass spectrometer and enters the the source region. Such a system prevents isotopic fractionation as the gas enters the high vacuum of the source region. Here the gas is ionized due to the heating of the filament (tungsten, rhenium, thoriated indium) to high temperature, bombardment the gas by the electrons, and production positively charged ions. These ions are accelerated by electric field which is created by application of a high voltage potential through a series of collimating electric lenses into electron beam which passes through a strong magnetic field in flight tube.

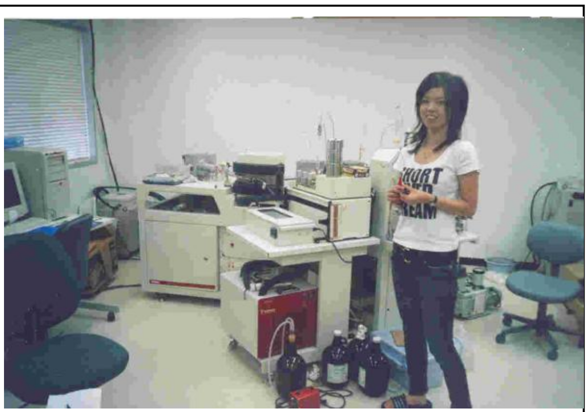
If an ion of mass m and charge z is accelerated in a potential U and injected into a uniform magnetic field B then the ion experiences a force and moves in a circular orbit of radius R. The motion is described by the *mass spectrometer equation*

$$m/z = B^2R^2/2U. \qquad (6.6)$$

For singly-charged ions the radius is determined by the choice of magnetic and electric field. The combination of electric and magnetic fields selects ions of particular mass and forms a mass filter. In such a way, ions are deflected in a circular trajectory: light ions are deflected more strongly than heavy ones. Thus the spatial separation of different isotopes of the same molecule is achieved. The voltage of the separated ions is measured in individual Faraday collectors; the relative voltage of the sample to standard is related to the isotopic composition of the sample gas.

The PRISM analytical and isotope ratio analyzer consists of ion optics, dual inlect system, manifold, HD option, differential pumping option, electronic units, high vacuum pumping system, electrical wiring assembly, mains switch and circuit breaker panel, utility inputs and output panels.





Dr. Ishita SACHIE
at the mass-spectrometer “PRISM”
Toyama University

Flight tube
of mass-spectrometer “PRISM”

An isotope composition of watersheds in Noko of Ishikawa was investigated also [Ishita Sachie, private communication]. Water composes light isotope $H_2{}^{16}O$ (99,731%), and heavy isotopes such as $H_2{}^{18}O$ (0.1999%), $H_2{}^{17}O$ (0.0369%), $HD^{16}O$ (0.0311%). It was shown that light isotopes are evaporated more quickly; if there are many heavy isotopes, the water reservoir disappears soon.

Weather Station

The simultaneous measurement and estimation of environmental parameters such as atmospheric pressure, wind speed and direction, temperature, humidity, and precipitation is realized with *weather station* – complex of barometer, anemometer and vane, thermometer, hygrometer, rain gauge which provide a useful information about weather or climate conditions either daily, or during each hour. Data of observations can be taken manually or automatically.

Prof. Kyoichi OTSUKI, Kyushu University, Japan, near weather station in Sasaguri region

Weather station in Kuju region

Connecting unit of weather station

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Part II. PHYSICS OF TRANSFER PHENOMENA

7. TURBULENCE TRANSFER

Turbulence

Turbulence is defined in the Merriam-Webster Online Dictionary as irregular atmospheric motion especially when characterized by up-and-down currents. *Turbulent flow* is characterized by chaotic changes of its parameters. *Laminar flow* occurs with no disruption between the layers.

The Reynolds number is used as criterium of transition between two regimes: laminar flow occurs at low Reynolds numbers, where viscous forces are dominant, while turbulent flow takes place at high Reynolds numbers.

Boundary Layer

Turbulence appears regularly in a relatively thin layer of the atmosphere which is called the *boundary layer*. It is characterized by heat, moisture or momentum transfer to or from the ground surface. The scale of turbulence varies from 100 m at night up to 4000 m during a day (in summer period in mid-latitudes). Turbulence induces the formation of *eddies* − currents of the air, moving contrary to the direction of the main current, especially in a circular motion. Air flow can be presented as a horizontal flow of numerous rotating eddies which consist of three dimensional components including vertical movement of the air. In spite of apparent chaotic character of the air flow its parameters can be estimated quantitatively due to covariance techniques.

Eddy Covariance

Eddy is a current of air, water, etc. moving against the main current and with a circular or whirlpool motion.

Covariance is a statistical measure of correlation of the fluctuations of two different quantities. Covariance quantifies the degree to which two variable vary together.

Eddy Covariance in the Environmental Biophysics is a method used to measure atmospheric fluxes of H_2O, CO_2, momentum, sensible and latent heat transferred due to the turbulence within the atmospheric boundary layer.

Let's discuss, for example, the wind speed with horizontal component u and vertical component υ which can be presented as

$$u = \bar{u} + \delta u; \quad \upsilon = \bar{\upsilon} + \delta\upsilon, \qquad (7.1)$$

where $\bar{u}$ and $\bar{\upsilon}$ are mean values of the wind speed components; δu and $\delta\upsilon$ are fluctuations of the wind speed components.

The covariance between two random variables u and υ is defined as

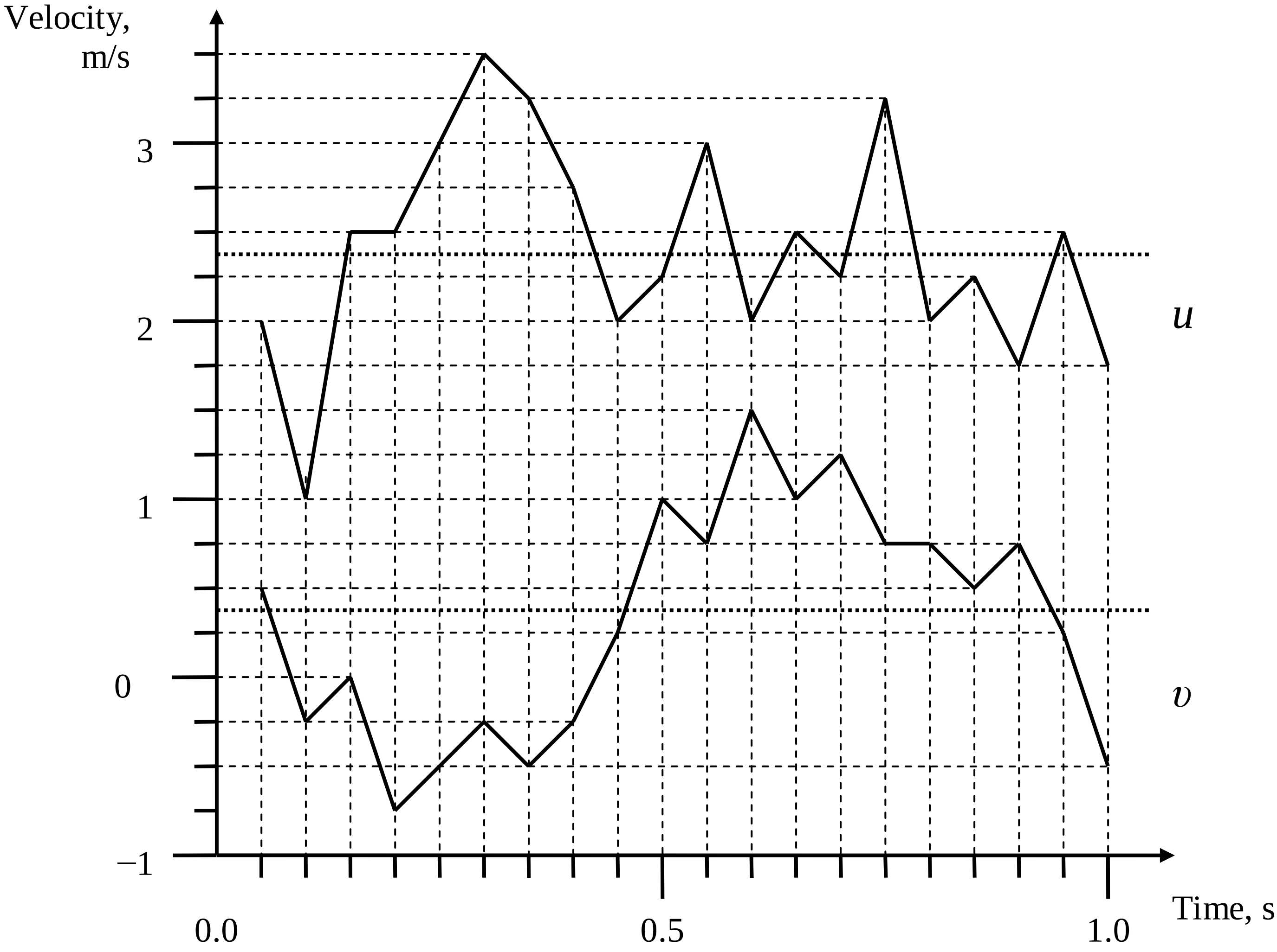
$$\mathrm{Cov}_{uw} = \frac{\sum u\upsilon}{n}, \qquad (7.2)$$

where n is a number of random variables.

By substituting (7.1) into (7.2) the covariance can be written as

$$\mathrm{Cov}_{uw} = \frac{\sum (u - \delta u)(\upsilon - \delta\upsilon)}{n}, \qquad (7.3)$$

Example: The fluctuations in horizontal component u and vertical component υ of wind are depicted in Figure below.



Let's calculate the covariance between horizontal component u and vertical component υ of wind speed according to the numerical data (Table 7.1):

Table 7.1. Results of calculation the covariance between horizontal component u and vertical component υ of wind speed

N	x	Y	$x - \bar{x}$	$y - \bar{y}$	$(x - \bar{x})(y - \bar{y})$
1	2	0.5	-0.4	0.19	-0.076
2	1	-0.25	-1.4	-2.6	3.64
3	2.5	0	0.1	-3.1	-0.31
4	2.5	-0.75	0.1	-3.85	-0.385
5	3	-0.5	0.6	-3.6	2.16
6	3.5	-0.25	1.1	-3.35	3.685
7	3.25	-0.5	0.85	-3.6	-3.06
8	2.75	-0.25	0.35	-3.35	-1.17
9	2	0.25	-0.4	-2.85	1.14

10	2.25	1	-0.15	-2.1	0.315
11	3	0.75	0.6	-2.35	-1.41
12	2	1.5	-0.4	-1.6	0.64
13	2.5	1	0.1	-2.1	-0.21
14	2.25	1.25	-0.15	-1.85	0.28
15	3.25	0.75	0.85	-2.35	-2.0
16	2	0.75	-0.4	-2.35	0.94
17	2.25	0.5	-0.15	0.19	0.029
18	1.75	0.75	0.65	-2.35	-1.53
19	2.5	0.25	0.1	-2.85	-0.0285
20	1.75	-0.5	-0.65	-3.6	2.34
$\overline{M}$	2.4	0.31			$\sum(x-x)(y-y)=$ =2.6494
σ^2	σ^2_x = 0.35	σ^2_y = 0.41			cov xy= $\frac{1}{N}\sum(x-x)(y-y)$ =2.6494/20=0.1324
Σ	σ_x = 0.59	σ_y = 0.64	$\sigma_x\sigma_y$ = 0.3776		r_{xy} = cov $xy/\sigma_x\sigma_y$ = =0.1324/0.3776=0.35

There are similarity and distinctions between coefficients of covariance and correlation.

Coefficient of covariance is positive if *y* increases with increasing *x*, negative if *y* decreases as *x* increases. Positive numbers of coefficient of correlation indicate they correlate directly and negative numbers indicate they correlate inversely. But the coefficient of covariance has no upper or lower limits, while coefficient of correlation can vary from +1, through zero, to –1. Usually the values of coefficient of correlation 0.00-0.30 indicates a weak correlation; 0.30-0.70 indicates a moderate correlation; 0.70-1.00 indicates a high correlation.

The results of our calculations (r_{xy}= cov$xy/\sigma_x\sigma_y$=0.35) mean that there is a moderate correlation between horizontal component *u* and vertical component υ of wind speed.

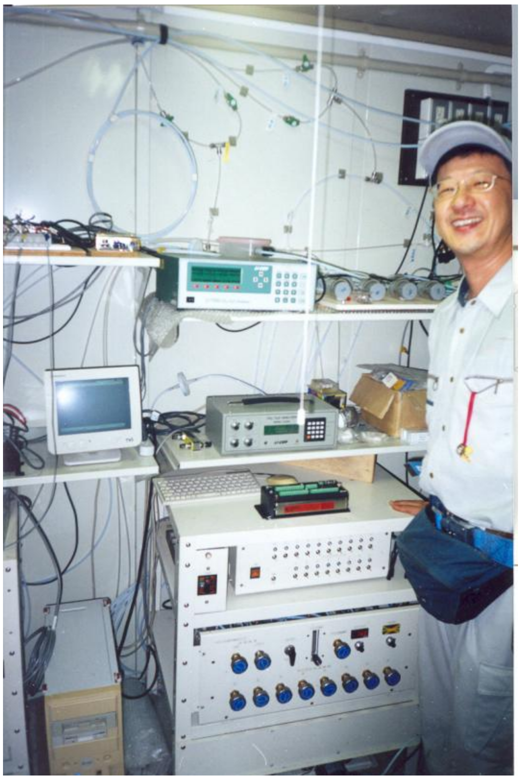
Turbulent Fluctuations

The bouindary layer is turbulent through its depth and all physical entities such as mass (concentration of H_2O or CO_2, aerosols), heat and momentum are transported in the vertical direction. One of the method of flux measurement is the eddy covariance.

The main principle of eddy covariance method is to measure measure vertical speed, the up and down movement, and and changes in concentration, density or temperature induced by fast turbulent fluctuations within atmospheric boundary layer. That’s why usually the eddy covariance system consists of three sensors which are used for measuring water vapour density, air temperature, and wind speed. This system foresees the application of an open-path infrared gas analyser (or a hygrometer) for estimation of water vapor density, and carbon dioxide density; a three-dimensional ultrasonic anemometer for measuring sonic temperature (which is approximately equal to the virtual temperature)and the wind speed in vertical and two mutually perpendicular horizontal directions.

This technique is mathematically complex, and makes it possible to provide computed elaboration data.

Kahoku Meteorological Tower, Japan



Dr Takanori SHIMIZU (Kyushu Research Center, Forestry and Forest Products Research Institute, Japan) at the base of Kahoku tower

A list of instruments that are installed in such a tower is given below.

Observation items	Levels / Depth	Instrument
Global solar radiation (incoming)	47.2m	Pyranometer (CM14, Kipp & Zonen, Netherland)
Global solar radiation (outgoing)	47.2m	Pyranometer (CM14, Kipp & Zonen, Netherland)
Long-wave radiation (incoming)	47.2m	Infrared radiometer (CNR1, Kipp & Zonen, Netherland)
Long-wave radiation (outgoing)	47.2m	Infrared radiometer (CNR1, Kipp & Zonen, Netherland)
Net radiation	47.2m	Net radiometer (NR-LITE, Kipp & Zonen, Netherland)
PPFD (incoming)	N/A	–
PPFD (outgoing)	47.2m	Quantum sensor (LI-190, LI-COR, USA)
Direct/diffuse radiation	51.0m	Pyranometer (CM3, Kipp & Zonen, Netherland) with shadow-band (PSB-100, Prede, Japan)
Direct/diffuse PPFD	N/A	–
Air temperature	51.0, 41.5, 34.0, 22.0, 10.5m	Platinum resistance thermometer (HMP45D, VAISALA, Finland/ ML-020L, EKO, Japan)
Humidity	51.0, 41.5, 34.0, 22.0, 10.5m	Capacitive hygrometer (HMP45D, VAISALA, Finland), Wet bulb temperature (ML-020L, Eko, Japan)
Soil temperature	0.05m	Thermistor (HOBO S-TMB-002, Onset, USA)
Soil heat flux	0.02m	Heat flow transducer (HFT-3.1, REBS, USA)
Soil water content	0.05m	Capacitance prove (ECH$_2$O, Decagon Devises, USA)
Wind speed	45.7, 41.7, 37.7m	3-cups anemometer (Met-One 014A,)
Wind direction	51.0m	Three-dimensional sonic anemometer-thermometer (DA600, KAIJO, Japan)
Barometric pressure	51.0m	Barometric pressure sensor (PTB210, VAISALA, Finland)
Precipitation	1.5m	Rain gauge: 0.5mm tipping bucket (RT-5, Ikeda Keiki, Japan)
CO_2 concentration	44.2, 38.5, 33.5, 27.0, 20.2, 13.5, 6.8, 1.0m	Closed-path CO_2/H_2O analyzer (LI-6262, LI-COR, USA)

Additionally, a radiometer is located above the canopy and soil heat flux sensor are installed into the ground.

Turbulent Velocity Fluctuations

Let's discuss, for example, the wind speed with horizontal component u and vertical component υ which can be presented as

$$u = \bar{u} + \delta u; \quad \upsilon = \bar{\upsilon} + \delta\upsilon , \qquad (7.4)$$

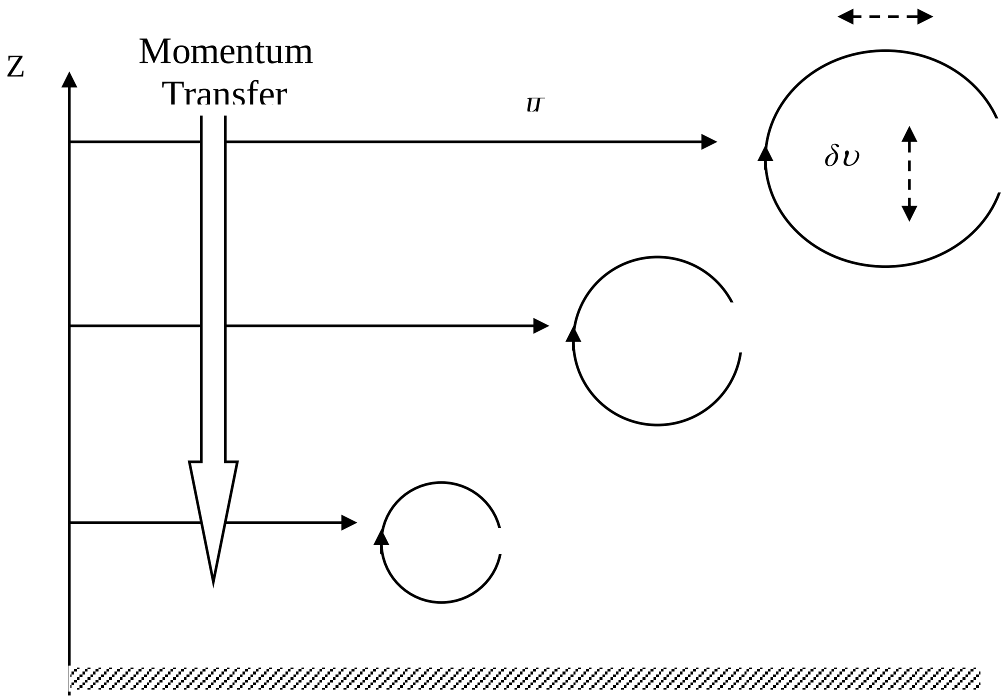
where $\bar{u}$ and $\bar{\upsilon}$ are mean values of the velocity components; δu and $\delta\upsilon$ are fluctuations of the wind speed components.

The time-averaged values of the fluctuations, according to Reynolds decomposition, equal zero

$$\overline{\delta u} = 0; \ \overline{\delta\upsilon} = 0. \qquad (7.5)$$

The average value of vertical wind speed equals zero

$$\bar{\upsilon} = 0. \qquad (7.6)$$



The Vertical Momentum Flux

The main principle of vertical flux estimation is the presentation of covariance between measurements of vertical momentum (or vertical momentum density) and vertical component of wind velocity

$$F = (\rho u)\delta\upsilon, \qquad (7.7)$$

where ρ is the density of air.

Mean momentum of a large number of air particles is defined as

$$F = \rho\overline{(\bar{u} + \delta u)(\bar{\upsilon} + \delta\upsilon)} =$$
$$= \rho\, (\bar{u}\,\bar{\upsilon} + \bar{u}\overline{\delta\upsilon} + \overline{\delta u}\,\bar{\upsilon} + \overline{\delta u\delta\upsilon}\,). \qquad (7.8)$$

As soon as $\bar{\upsilon}$ = 0 and $\overline{\delta u}$ = $\overline{\delta\upsilon}$ = 0 (see Equations (7.5)–(7.6), the last equation can be transformated as

$$\boxed{F = \rho\,(\overline{\delta u\delta\upsilon}\,)} \qquad (7.9)$$

Here the density fluctuations over flat and vast space is assumed negligible.

Sensible Heat Flux

The direct transfer of heat from the surface to the atmosphere through conduction and convection is called *sensible heat.* This heat flux results from a temperature gradient between the Earth's surface and the atmosphere.

Sensible heat flux is equal to the mean air density multiplied by the covariance between fluctuations in instantaneous vertical wind speed and temperature

$$\boxed{H = \rho_a C_P \overline{\delta\upsilon\delta T_a}} \qquad (7.10)$$

where ρ_a is air density; C_p is specific heat capacity of air at a constant pressure; $\delta\upsilon$ is the instantaneous fluctuation of vertical wind speed; δT is the instantaneous fluctuation of air temperature.

Latent Heat Flux

The energy flux to the atmosphere carried by water vapour through evaporation and transpiration from the surface is called *latent heat.* This heat causes the changes of the state of the substance (for example, water can become vapour) with no change in temperature of a substance.

Latent heat flux λE can be defined as the covariance between fluctuations in instantaneous vertical wind speed and water-vapour density

$$\boxed{\lambda E = L_V \frac{\rho_a}{\rho_w}{}_V \overline{\delta\upsilon\delta\rho_v}} \qquad (7.11)$$

where L_v is the latent heat (hidden heat) of vaporization (corresponding to the liquid-to-gas phase change); ρ_a is air density; ρ_w is water vapour density; $\overline{\delta\rho}$ is the fluctuations of the water vapour density.

Carbon Dioxide Flux

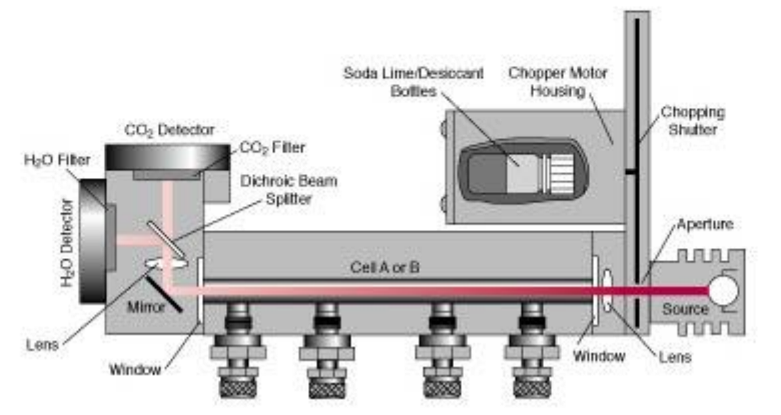
Carbone Dioxide Flux can be presented as the mean covariance between fluctuations of vertical wind speed and density of CO_2 in the air.

$$\boxed{F_C = \overline{\delta\upsilon\delta\rho_c}} \qquad (7.12)$$

Typical eddy covariance system that is settled in Kahoku Meteorological Station consists of closed-path system (LI-7000, LI-COR, USA) for measuring CO_2 flux, open-path system (LI-7500, LI-COR, USA) for measuring H_2O flux, three-dimensional sonic anemometer-thermometer (DA600-3T, KAIJO, Japan) for measuring wind speed and air temperature. Measurement height is 51 m; sampling frequency is 10 Hz; system is equipped with data logger and data storage.

Gas Analysers

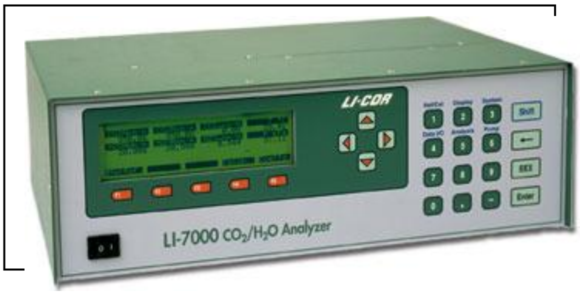
Closed-path system (LI-7000, LI-COR). This dual cell, differential CO_2/ H_2O Gas Analyser consists of source of infrared radiation, chopper, optical system (lens, mirror, filters), cell, splitter of a beam, and two detectors (for CO_2 and H_2O). Absorption at wavelengths centered at 4.26 µm and 2.59 µm provide for measurement of CO_2 and water vapor, respectively. The LI-7000 CO_2/ H_2O Gas Analyzer is a differential analyzer, in which a known concentration (which can be zero) gas is put in the reference cell, and an unknown gas is put in the sample cell. The LI-7000 CO_2/ H_2O Gas Analyzer is a differential analyzer, in which a known concentration (which can be zero) gas is put in the reference cell, and an unknown gas is put in the sample cell.



Closed-path system LI-7000. From http://www.licor.com/env/PDF_Files/LI7000.pdf

The LI-7000 CO_2/ H_2O Gas Analyzer is a differential analyzer, in which a known concentration (which can be zero) gas is put in the reference cell, and an unknown gas is put in the sample cell. The instrument software provides continuous measurement of the absolute concentration in the sample cell as well as the differential concentration.

LI-7000 Infrared Gas Analyzer



Specifications
Gas pressure: maximum allowable pressure is 115 Pa
CO_2 range: 0–3000 ppm
Accuracy: 1% nominal
H_2O range: 0–60 mmol/mol
Accuracy: 1%
Temperature range: 0–50 ^0C ambient
Wigth: 8.8 kg.

Open-path system (LI-7500, LI-COR). This device is based on the measurement of a carbon dioxide density and water vapor density due to detecting the absorption of infrared radiation by CO_2 and H_2O in the infrared radiation path. Combination of optics, electronics, and software makes it possible to provide fast and precise measurements of *in situ* densities of CO_2 and H_2O in turbulent air structures and to use these data in conjunction with sonic anemometer turbulence data to determine the fluxes of CO_2 and H_2O by eddy covariance techniques.

Principle of operation is based on measuring the absorption of infrared radiation at different wavelengths – one at a wavelength that is absorbed by the gas (4.26 μm for CO_2 and 2.59 μm for H_2O), and the other at a non-absorbing reference wavelength (3.95 μm for CO_2 and 2.40 μm for H_2O).

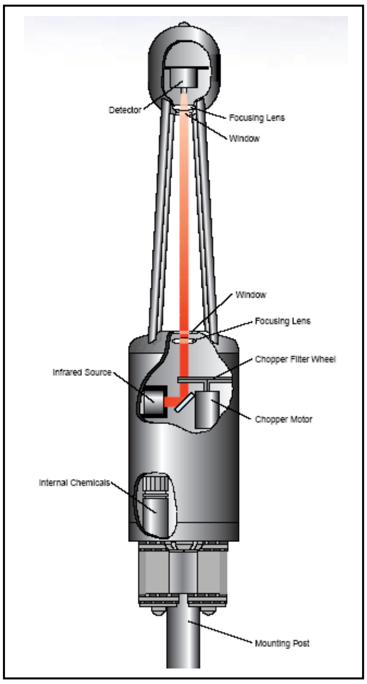
The LI-7500 sensor head has a 12.5 cm open path; a source of infrared radiation emits an infrared beam of 1 cm diameter which is modulated at 150 Hz to avoid the effect of ambient light on operation of the head. This beam goes through 12.5 cm open path and enters a cooled lead selenide detector.

The flux of CO_2 or H_2O from a landscape is obtained from the vertical wind speed (measured with a sonic anemometer) and the concentration of the eddy (measured with the LI-7500).

LI-7500 Infrared Gas Analyzer

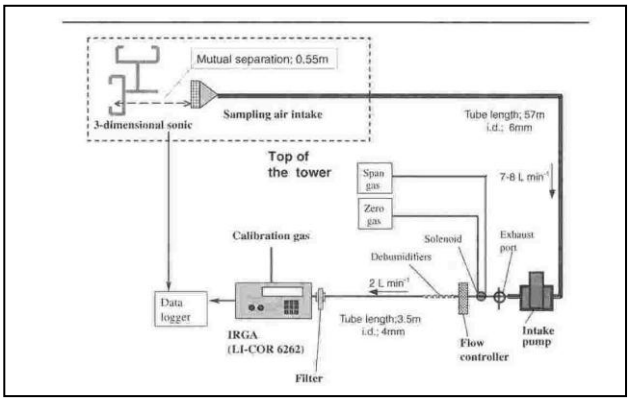
Specifications
Type: Absolute, open-path non-dispersive infrarted gas analyzer

Detector: Thermo-electrically cooled lead selenide
Bandwidth: 5, 10, or 20 Hz, software selectable
Temperature Range: –25 to 50 ^{0}C
Dimensions: Head6.5×30 cm; Control Box: 35×30×15 cm
Weight: Head 0.75 kg; Controil Box 4.8 kg



Head of LI-7500 Infrared Gas Analyzer
http://www.licor.com/env/PDF_Files/LI7500.pdf

Three-dimensional sonic anemometer-thermometer (DA600-3T, KAIJO, Japan) is used in Kahoku Meteorological Station. Principle of operation of ultrasonic anemometer is described in Section “Wind”.



Schematic image of the Kahoku experimental watershed sampling system
From (Shimizu, 2007)

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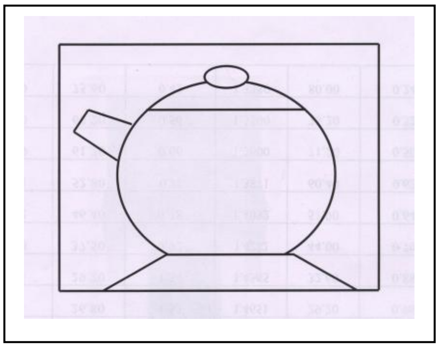
8. ENTROPY TRANSFER

Thermodynamic System

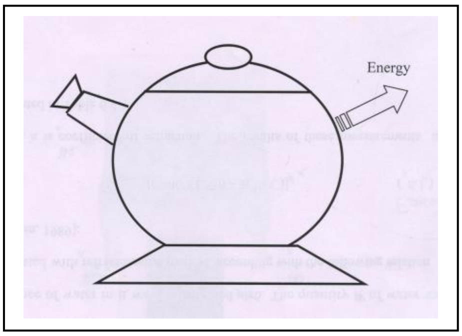
Thermodynamic system is the complex of macroscopic bodies that can interact with each other and other bodies (surroundings) through exchange by energy and matter between them. It is a part of universe that is separated from the rest by boundary.

All thermodynamic systems can be classified as:

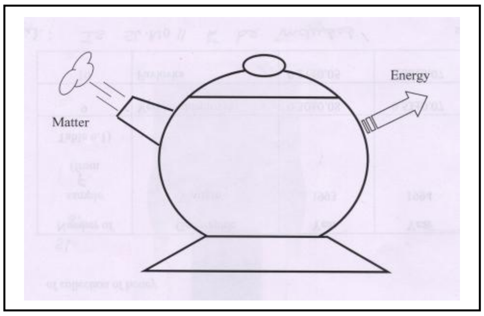
- *isolated system* when it can exchange neither energy nor matter with its surroundings.



- *closed* system when it can exchange energy but cannot exchange matter with its surroundings.



- *open system* when it can exchange either energy or matter with its surroundings.

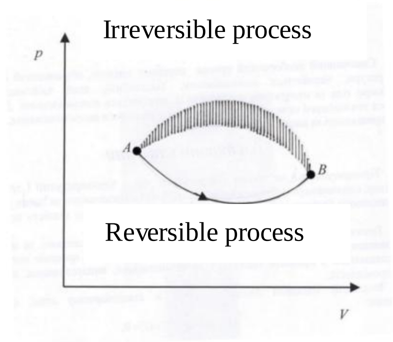


Each thermodynamic system is characterised by certain *thermodynamic parameters* – pressure p, temperature T, volume V.

Transfer of thermodynamic system from one state to another is called *thermodynamic process.*

Reversible and Irreversible Processes

A *reversible process* is defined as a succession of equilibrium states if the system passes from the initial state to the final state. The process is reversible if the system can return to its initial state without any residual exchanges in its surroundings. A reversible process can be depicted in (p,V) system of coordinate as a line.



An *irrevesible process* passes through a series of nonequilibrium states and is accompanied with the irreversible changes; the system and its surroundings cannot be returned to their initial states. All real processes in nature are irreversible.

The First Law of Thermodynamics

The *First Law of Thermodynamics* presents a generalized law of conservation of energy; it considers the possible changes of the internal energy ΔU, heat Q and work W. Let's discuss thermodynamic system that participates in the transition from the initial state to the final state; during this transition heat is absorbed (or removed) and work is done by system (or done on the system).

It is shown that according to the law of conservation of energy the transition of the system that undergoes an infinitesimal change from the initial state to the final state the small change in internal energy dU can be expressed as

$$dU = dQ - dW. \quad (8.1)$$

where dQ is a small amount of heat; dW is a small amount of work.
Here $dW > 0$, if work is done by system and $dW < 0$ if work is done on the system.

$$dU = dQ - pdV. \quad (8.2)$$

Here the elementary work dW done during the expanding gas is defined as follows

$$dW = Fdx = -pAdx = -pdV. \quad (8.3)$$

where F is the force (for example, exerted by the gas on the piston of cross-sectional area A); p is a pressure on the cylinder walls and piston; dV is the change in volume of the gas.

Let's consider some situations.

1. *Isolated system* doesn't interact with its surroundings, that's why thermal flow is absent (dQ = 0) and work is zero (dW = 0). Hence, dU = 0 and internal energy is constant (U = const).

2. *Closed system* which exchanges energy but not the matter

$$dU = dQ + dW_r. \quad (8.4)$$

3. Open system is characterized with the flow of matter during transport processes or chemical reactions

$$dU = dQ + dW + dU_{matter}. \quad (8.5)$$

or

$$dU = dQ - pdV + \sum_{1}^{n} \mu_k dN_k , \quad (8.6)$$

where μ_k– chemical potential that corresponds to free energy per mole of species *k*. It is known that living organisms require a continual input of free energy (first of all, energy of sun); without this free energy organism stops its vital activity. This free energy under conditions of constant temperature and pressure is known as the *Gibbs free energy*
$G = \sum_k n_k \mu_k$.

EQUILIBRIUM THERMODYNAMICS

Entropy and its Properties

Rudolf Clausius wrote in 1865: "I propose to call the magnitude *S* the *entropy* of the body from the Greek word *τροπη* – transformation". He postulated also that this function *S* depends only on the initial and final states of a reversible process. For example, if S_A and S_B are the values of this function in the states *A* and *B*, a function S depends only on the initial and final states *A* and *B* of a re4versible process

$$S_B - S_A = \int_A^B \frac{dQ}{T} \quad (8.7)$$

where *dQ* – elementary heat that is absorbed by the system during small change of its state; *T* is temperature of heater.

The change in entropy, *dS*, between two equilibrium states is equal to the heat transferred, *dQ*, divided by the absolute temperature, *T*, of the system in this interval.

$$dS = \frac{dQ}{T}. \quad (8.8)$$

For an irreversible process the system expels more heat to the surroundings and the entropy increases

$$dS > \frac{dQ}{T}. \quad (8.9)$$

Classical (*equilibrium*) *thermodynamics* describes systems which are in equilibrium or are undergoing *reversible* processes. Equilibrium systems are maintained without an exchange of energy or matter.

The main tendencies of the change of entropy can be formulated as:

1. *Entropy changes in a reversible process is zero; entropy remains constant in the isolated system during the reversible processes*

$$dS = 0; S = \text{const.} \quad (8.10)$$

2. *Entropy increases in the isolated system during the irreversible processes and reaches the maximal value*

$$dS > 0. \quad (8.11)$$

In such a way, any process in isolated system is accompanied with the increase of entropy

$$\boxed{dS \geq 0.} \quad (8.12)$$

NONEQUILIBRIUM THERMODYNAMICS

Nonequilibrium thermodynamics describes *dissipative* systems; these systems are maintained only through the of energy or matter; as soon as living systems are typically dissipative structures nonequilibrium thermodynamics applies the formulations of thermodynamics to quantitative investigations of the processes of living systems.

Stationary State

Living organisms are open thermodynamic systems that exchange either energy or matter with its surroundings. These organisms are able to absorb the energy, nutrients, to take part in gas exchange, to do work, to expel the products of metabolism. Thus, the viability of living organism presents the set of nonequilibrium processes. The result of such exchange of living organism with its surroundings is achievement of *stationary state,* which is characterised by the constant physical and chemical properties of thermodynamic system in spite of the absence of thermodynamic equilibrium. The models of nonequilibrium and stationary states can be presented graphically (Figure). There are here the input flux and output flux of liquid, but the level of this liquid in reservoir is stable.

The Entropy Change

The entropy change *dS* which was introduced in classical thermodynamics can be presented as a sum of two parts in nonequilibrium thermodynamics:

$$dS = d_eS + d_iS, \quad (8.13)$$

where d_eS – the change of the system's entropy due to exchange of energy and matter with the surroundings; d_iS – the change in entropy due to irreversible processes within the system.

The entropy changes d_eS and d_iS can be expressed for different thermodynamic systems:

For *isolated system*:

$$d_eS = 0 \text{ and } d_iS \geq 0. \quad (8.14)$$

For *closed system*:

$$d_eS = \frac{dQ}{T} = (dU + pdV)/T \text{ and } d_iS \geq 0. \quad (8.15)$$

For *open system*:

$$d_eS = (dU + pdV)/T + dS_{реч} \text{ and } d_iS \geq 0, \quad (8.16)$$

where $dS_{реч}$ – the change of entropy due to matter exchange with the surroundings.

Thus, the expression for the entropy exchange due to irreversible processes is valid for each thermodynamic system – isolated, closed, or open one

$$\boxed{d_iS \geq 0} \qquad (8.17)$$

This is the statement of the *Second Law of Thermodynamics* in the most general form (Prigogine).

The entropy change d_iS due to irreversible processes in living organism can reach positive values only according to the Second Law.

The entropy change d_eS due to the exchange with the exterior can be positive, negative or equal zero.

If $d_eS \geq 0$ corresponds, for example, the disintegration of complex biological formations into simple structures which is accompanied with the cessation of vital processes and life as a whole.

If $d_eS<0$ and $|d_eS| > |d_iS|$, total change of entropy becomes negative; this situation means complication of system organization, formation of more complex compounds, growth of tissues etc.

In sucjh a way, contrary to equilibrium thermodynamics of isolated systems, which determines the entropy of equilibrium states only, nonequilibrium thermodynamic (of open systems) introduces the term of entropy flow.

Thermodynamic Forces and Thermodynamic Flows

One of the important achievements of thermodynamics of irreversible processes is that the temporal changes of entropy is discussed (For example, growth or aging of living organism).

Differentiation of equation (13) leads to the expression:

$$\frac{dS}{dt} = \frac{d_eS}{dt} + \frac{d_iS}{dt} \ . \qquad (8.18)$$

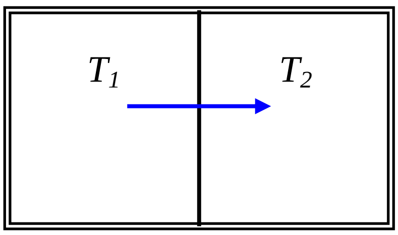
Here $\frac{dS}{dt}$ is called the *rate of entropy production*. The whole rate of entropy production in open system is equal a sum of entropy flow $\frac{d_eS}{dt}$ through the open system and the rate of entropy production $\frac{d_iS}{dt}$ due to irreversible processes inside the system.

Balance of entropy in stationary state of the system is determined as:

$$\frac{dS}{dt} = \frac{d_eS}{dt} + \frac{d_iS}{dt} = 0, \qquad (8.19)$$

Thus, a stationary state implies that the total entropy S of the system is constant.

Let's consider as an example of the relation of entropy change and irreversible processes an isolated system that consists of two parts of unequal temperature ($T_1>T_2$).



$$dQ$$

Here dQ is amount of heat that flows from first part to second one during period of time dt. As soon as this is isolated system, $d_eS = 0$. The volumes of each part are constant also, that's why $dW = 0$.

The First Law of Thermodynamics can be written for each part as

$$dU_1 = dQ_1;\ dU_2 = dQ_2. \qquad (8.20)$$

Since the heat lost $(-dQ_1)$ by first part of the system is equal to the heat gain (dQ_2.) by the second part, we can write

$$-dQ_1 = dQ_2 = dQ. \qquad (8.21)$$

The total change in entropy due to the irreversible processes, d_iS, can determined as

$$d_iS = -\frac{dQ}{T_1} + \frac{dQ}{T_2} = \left(\frac{1}{T_2} - \frac{1}{T_1}\right)dQ\,. \qquad (8.22)$$

The rate of entropy production can be obtained by dividibg last equation by dt

$$\frac{d_iS}{dt} = \left(\frac{1}{T_2} - \frac{1}{T_1}\right)\frac{dQ}{dt}. \qquad (8.23)$$

Conclusion: the rate of entropy production due to irreversible processes $\frac{d_iS}{dt}$ is a product of the thermodynamic force F_k (the difference of inverse of temperature $\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$) and thermodynamic flow $J_Q = \frac{dQ}{dt}$.

If several k irreversible processes take place simultaneously within a system, the entropy change and the rate of entropy production due to irreversible processes can be written as

$$d_iS = \sum_k F_k dX_k \geq 0; \qquad (8.24)$$

$$\frac{d_iS}{dt} = \sum_k F_k \frac{dX_k}{dt} = \sum_k F_k J_k \geq 0. \qquad (8.25)$$

In such a way, all irreversible processes can be presented in terms of *thermodynamic force F* (cause of the process such as difference in temperature or concentration, electrical or chemical potential etc.) and the *thermodynamic flow X* (velocity of the process such as heat flow, diffusion, current flow, chemical reaction etc.).

When a system is close to equilibrium, there is linear relations between the moving forces and flows that are induced by these forces; each flow can be presented as linear combination of moving forces (*Linear Law of Thermodynamics of Irreversible Processes)*:

$$J_k = \sum_{j=1}^{N} L_{kj} F_j\,, \qquad (8.26)$$

where J_k – are flows; L_{kj} – phenomenological coefficients; F_j – driving forces (gradients), N – general number of moving forces in the system.

Transport Phenomena

Irreversible processes that induce in physical system the spatial transport of entropy, mass, momentum, electric charges and so on, are called *transport phenomena*.

Thus, the process of diffusion (mass transfer) can be described with $J_m = \frac{dm}{Sdt}$; $L_m = -D$; $F_m = \frac{d\rho}{dx}$, where m – mass of the material that diffuses during the time interval dt across the area S; D – coefficient of diffusion; $\frac{d\rho}{dx}$ – the density gradient. The *Fick's Law* for mass transport of material is the following:

$$J_m = L_m \cdot F_m \qquad (27)$$

or

$$J_m = \frac{dm}{Sdt} = -D\frac{d\rho}{dx}. \qquad (28)$$

The SI units of the flux density of material is $kg/m^2 \cdot s$; coefficient of diffusion – m^2/s; density gradient – $kg/m^3 \cdot m$.

The process of thermal conductivity (heat transfer) is described with $J_q = \frac{dQ}{Sdt}$; $L_q = -k$; $F_q = \frac{dT}{dS}$, where $\frac{dQ}{Sdt}$ – heat flux density (quantity of heat that is transferred due to thermal conductivity during the time interval dt across the area S;); k – coefficient of thermal conductivity; $\frac{dT}{dS}$ – temperature gradient. Thus it is possible to obtain the *Fourier's Law*:

$$J_q = L_q \cdot F_q \qquad (8.29)$$

or

$$J_q = \frac{dQ}{Sdt} = -k\frac{dT}{dS}. \qquad (8.30)$$

The SI units of the heat flux density of material is $J/m^2 \cdot s = W/m^2$; coefficient of thermal conductivity – $W/m \cdot K$; temperature gradient – C/m.

If the parallel layers of the gas or liquid are transferred with different moduli of velocity the friction force appears between them and momentum transfer occurs. The process of momentum transfer is described with $J_p = \frac{dp}{Sdt}$; $L_p = -\eta$; $F_p = \frac{d\upsilon}{dx}$, where $\frac{dp}{Sdt}$ – momentum flux density; η – coefficient of internal friction (viscosity); S – area through which the momentum is transferred; $\frac{d\upsilon}{dx}$ – velocity gradient. This process is described by the *Newton's Law*:

$$J_p = L_p \cdot F_p \qquad (8.31)$$

or

$$J_p = \frac{dp}{Sdt} = -\eta\frac{dV}{dx}. \qquad (8.32)$$

The SI units of the momentum flux density is N/m^2; coefficient of internal friction – N·s/m^2; velocity gradient – 1/s.

Fluid (water) flow in a porous medium (soil) is described by the *Darcy,s Law*:

$$J_в = L_\psi \cdot F_\psi \qquad (8.33)$$

or

$$\frac{dQ}{dt} = -K(\psi)A\frac{d\psi}{dx}. \qquad (8.34)$$

Here $J_p = \frac{dQ}{Sdt}$; $L_\psi = -K(\psi)$; $F_\psi = \frac{d\psi}{dx}$, where $\frac{dQ}{Sdt}$ – density of water flow; $K(\psi)$ – hydraulic conductivity; A – area through which the water flow is transferred;; $\frac{d\psi}{dx}$ – water potential gradient.

The SI units of the water flux density is kg/m^2·s; hydraulic conductivity – kg·s/m^3; gradient of water potential – J/kg·m or m/s^2.

Let's discuss the flow of electrons in conductor with the assumption that the density of electrons and temperature are characterised by the uniform distribution. Electric current as the flow of electrons is proportional to the applied voltage and inversely proportional to the electrical resistance of conductor. This relations are called the *Ohm's Law,* which can be written in differential form as:

$$J_e = L_e \cdot F_{qe} \qquad (8.35)$$

or

$$j = \sigma E = \sigma\frac{d\varphi}{dx}. \qquad (8.36)$$

Here $J_e = j = \frac{I}{S}$ – current density; $L_e = \sigma = \frac{1}{\rho}$ – conductivity of the conductor; ρ – resistivity; $F_e = E = \frac{d\varphi}{dx}$ – electric field; $\frac{d\varphi}{dx}$ – potential gradient.

The SI units of the current density – A/m^2; conductivity – s^3·A^2/m^3·kg; electric field – J/C·m = m·kg/A·s^3.

It is necessary to mention that linear law is valid for relatively small deviation of the system from the state of equilibrium.

The *Hagen-Poiseuille equation* is a physical law that describes slow viscous incompressible flow through a constant circular cross-section.

$$J_V = L_V X_V \qquad (8.37)$$

or

$$J_в = \frac{dV}{dt} = \left(\frac{\pi r^4}{8\eta l}\right)\Delta p, \qquad (8.38)$$

where V is a volume of the liquid poured (cubic meters); t is the time (seconds); R is the internal radius of the tube (meters); Δp is the pressure difference between the two ends (pascals); η is the dynamic fluid viscosity (Pa·s); L is the total length of the tube in the x direction (meters).

We shall discuss in the following chapters the application of "magic" equation (8.26) to various transport phenomena which occur in living organisms and its surroundings.

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9. MASS TRANSFER: WATER AND SOLUTES

This process is related to the movement of mass from one place of the environment or environmental component to another one. Mass transfer occurs in living cells, soil, plants, atmosphere, watersheds. Let's consider mass transfer phenomena in soil-plant-atmosphere system.

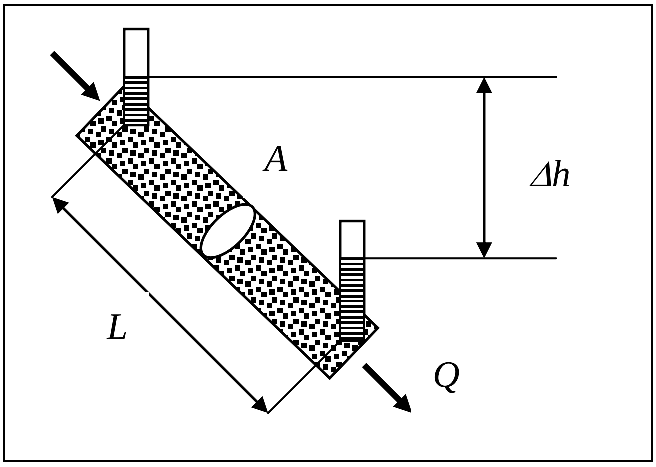
Mass Transfer in Soil

Soil usually consists of solid (inorganic and organic components), liquid (water), and gaseous (mostly N_2, O_2, CO_2, and water vapor) phases. Soil particles, water and dissolved minerals such as Na, K, Ca, Mg, Cl, NO_3, SO_4, HCO_3, form *soil solution.* The open spaces between solid particles of the soil are called *pores* which represent irregular and tortuous tubes. Pore size can vary from more than 1000 μm (macropore) to 10-1000 μm (mesopore) and less than 10 μm (micropore).

The movement of liquid through porous material was described by *Darcy's Law* in 1856; this law can be expressed as

$$q = \frac{dQ}{Sdt} = -K\frac{h_2 - h_1}{L}, \qquad (9.1)$$

where q is the rate of flow through the porous medium (filter sand); $\frac{dQ}{Sdt}$ – the specific discharge of water; Q – volume of water; K – coefficient of proportionality (hydraulic conductivity); A – cross-sectional area to flow; t – time; $\Delta h = h_2 - h_1$ – difference of water heights above a reference level measured by manometers; L – length of the flow path; $\frac{\Delta h}{L}$ – hydraulic gradient.



In such a way, the water flow depends on the pressure gradient; this flow is directed from high pressure towards low one:

$$q = -K\frac{\Delta h}{L}. \qquad (9.2)$$

Here $\frac{\Delta h}{L}$ is called head gradient across porous medium.

In saturated and uniform soil hydraulic conductivity K is constant; the value of this proportionality factor depends on the type of soil: 10^{-4}–10^{-5} m/s for sandy soils and 10^{-6}–10^{-9} m/s for clayey soils.

Darcy's law can be written in terms of water potential ψ that is causing the water flow:

$$q = \frac{dQ}{dt} = -K(\psi)A\frac{d\psi}{dx}. \qquad (9.3)$$

or in the form of generalized equation

$$J_w = L_\psi \cdot F_\psi \qquad (9.4)$$

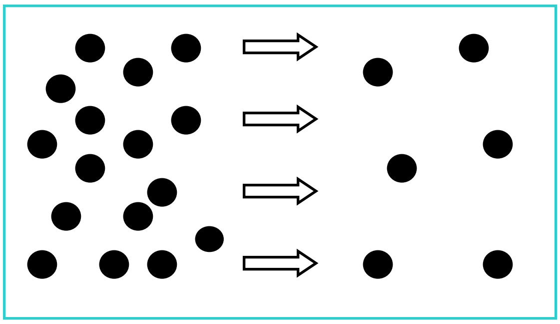
Here $J_p = \frac{dQ}{Sdt}$ – density of water flow; $L_\psi = -K(\psi)$ – hydraulic conductivity; $F_\psi = \frac{d\psi}{dx}$ – water potential gradient.

The SI units of the water flux density is $kg/m^2 \cdot s$; hydraulic conductivity – $kg \cdot s/m^3$; gradient of water potential – $J/kg \cdot m$ or m/s^2.

In general, Darcy's law is valid for slow and viscous flows such as groundwater flows.

Molecular Diffusion

Diffusion is the movement of substance molecules from an area where their concentration is high to an area that has low concentration. In soil, diffusion means the net motion of solute molecules through pores; in plant cells diffusion is responsible for transport of water and solutes across cell membrane down a concentration gradient.



Diffusion occurs as a result of the Second Law of Thermodynamics which states that the entropy of any system must always increase with time.

The process of diffusion can be described by the *Fick's First Law*

$$J_m = \frac{dm}{Adt} = -D\frac{dc}{dx}. \qquad (9.5)$$

or in generalized form

$$J_m = L_m \cdot F_m, \qquad (9.6)$$

where $J_m = \frac{dm}{Sdt}$ is diffusive flux (the rate at which mass is transported per unit area); $L_m = -D$ is diffusion coefficient; $F_m = \frac{dc}{dx}$ – concentration gradient; m – mass of the material that diffuses during the time interval dt across the area A.

The SI units of the flux density of material is $kg/m^2 \cdot s$; coefficient of diffusion – m^2/s; concentration gradient – $kg/m^3 \cdot m$.

The change of solute concentration with position and time as result of diffusion is described by the *Fick's Second Law*:

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2}. \qquad (9.7)$$

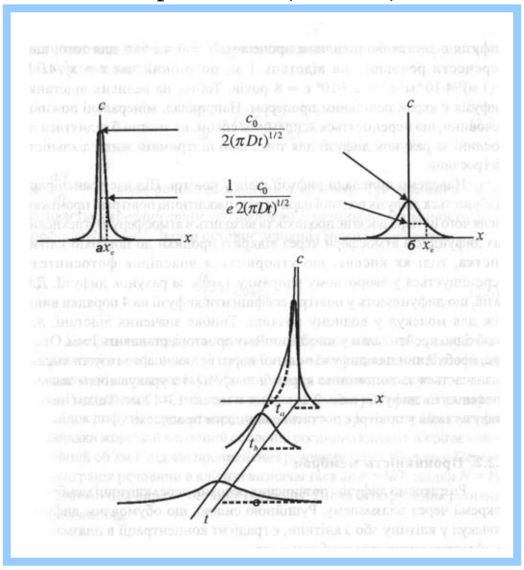
The solution of this equation can be found as:

$$c = \frac{c_0}{2(\pi Dt)^{1/2}} e^{-x^2/4Dt}, \qquad (9.8)$$

where c_0 – amount of solute that passes at the moment of time $t = 0$ through unit area which is placed at the origin of x-direction (i.e., at $x = 0$), and c is the concentration at the position x at any later moment of time t.

It is seen that concentration is equal $\frac{c_0}{2(\pi Dt)^{1/2}}$ at the initial point ($x = 0$). The distance x_e from the initial point at which the concentration drops to $1/e$ (or 37%) of its origin value is equal $x_e = (4Dt)^{1/2}$.

Dependence of concentration of particles on their position from the initial point



The typical values of coefficient of diffusion of small molecules in water solution and gases in air is given in Table 9.1.

9.1. The typical values of coefficient of diffusion of small molecules in water solution and gases in air [Nobel,2005]

Substance	Coefficient of diffusion, m^2/s	Substance	Coefficient of diffusion, m^2/s
Glucose	$0.67\cdot10^{-9}$	Na^+ (with Cl^-)	$1.5\cdot10^{-9}$
Glycin	$1.1\cdot10^{-9}$	CO_2 (in solute)	$1.7\cdot10^{-9}$
Sucrose	$0{,}52\cdot10^{-9}$	CO_2 (gas)	$1.51\cdot10^{-5}$
Ca^{2+} (with Cl^-)	$1.2\cdot10^{-9}$	H_2O	$2.42\cdot10^{-5}$
K^+ (with Cl^-)	$1.9\cdot10^{-9}$	O_2	$1.95\cdot10^{-5}$

Let's estimate what the interval of time is necessary to take for small molecules in aqueous solution to diffuse the distance 50 μm which is equal the typical size of leaf cell. The coefficient of diffusion is $D = 10^{-9}$ m^2/s. This interval of time is determined as $t = x_e^2/4D = (50\cdot10^{-6}\ m)^2/4\cdot10^{-9}\ m^2/s = 0{,}6$ s. Thus, the process of diffusion is quite rapid process for the subcellular distances. But if it is necessary to pass the distance 1 m the time interval is equal $t = x_e^2/4D = (1\ m)^2/4\cdot10^{-9}\ m^2/s = 2{,}5\cdot10^8\ s \approx 8$ years. It means that diffusion is a rather slow process over long distances.

Osmosis

The diffusion of water from the soil into the root xylem through the cell membrane that is driven by a difference in solute concentration on the two sides of this membrane is called *osmosis*. A selectively permeable membrane provides the passage of water but not solute molecules or ions; in such a way, osmosis is the transport of water from a region of high water concentration (pure water) through a semi-permeable membrane to a region of low water concentration or a solvent through a semi-permeable membrane from a region of low solute concentration to a region of high solvent concentration.

The osmotic pressure p_{osm} of a dilute solution can be calculated using the *Formula of Van't Hoff:*

$$p_{osm} = RTC_A, \qquad (9.9)$$

where R – the gas constant (R = 8.31 J·mol^{-1}·K^{-1} or R = 0.08206 L · atm · mol^{-1} · K^{-1}); T – absolute temperature; C_A – molar concentration of solute.

Water potential

The potential energy of water relative to pure water (e.g. deionized water) in reference conditions is called *water potential*. It is necessary to mention the most general peculiarities of water potential:

Pure water has a water potential of zero and cannot absorb water; addition of solutes lowers water potential into the negative range; solutions can absorb water. The stronger the solution, the more negative water potential. Any solution at atmosphere pressure has a negative water potential. In terms of osmosis water moves across a membrane from the solution with higher water potential to the solution with the lower water potential.

Water molecules in solution are restricted in the movement due to the formation specific shells by water molecules around the solute in comparison with pure water; that's why the addition of solutes lowers the water potential.

Water potential is highest when water is a liquid and lowest when water is a gas in air.

Water potential is directly proportional to pressure.

Short-Distance Transport in Plants

Epidermis forms the boundary between the plant and the external world. The epidermis serves several functions: protection against water loss, regulation of gas exchange, secretion of metabolic compounds, and (especially in roots) absorption of water and mineral nutrients. Most absorption occurs near the root tips where the epidermis is permeable to water.

Root hair cells massively increase the surface area of the root. They are responsible for the uptake of water (by osmosis) and mineral ions (mainly by active transport) from soil into the root.

The total number of the root hairs can reach $1.4\cdot10^{10}$ (rye) and surface area about 631 m^2; this surface area constitutes 60 % of the total surface of the root system.

Normally water enters roots by simple diffusion. Cells cannot absorb a sufficient supply of mineral ions by diffusion alone – the soil solution is too dilute. Minerals enter roots due to the active transport.

Active transport is the process by which dissolved molecules (solutes) move across a cell membrane from a lower to a higher concentration. It permits root cells to accumulate essential minerals in very high concentrations. See the site http://www.bbc.co.uk/schools/gcsebitesize/biology/cellprocesses/2diffusionandosmosisrev4.shtml which explains the participation of carrier proteins that pick up specific molecules and tae them through the cell membrane against the concentration gradient.

Plasma membrane consists of such an important active transporter as the *proton pump* which provides the release of energy to pump hydrogen ions (H^+) out of the cell through hydrolysis of ATP. Concentration of H^+ ions becomes higher outside than inside; this situation leads to the formation of more negative potential outside the cell in comparison to the inside. For example, the uptake of potassium ions (K^+) by root cells from the soil is realised due to proton pump action against a ten-thousand-fold concentration gradient.

Soil solution flows into hydrophilic walls of epidermal cells and passes through the apoplast into root cortex.

The Apoplast Route

Apoplast is the free diffusional space between either the cells or in the cells walls themselves outside the plasma membrane. Apoplast route is used for transport of water ans solutes through the roots to the stele. This route is interrupted by the *Casparian strip* – material in the radial and transverse walls of the endodermis which realizes the passage of substances through at least one membrane and prevents the leakage of stele contents back into apoplast and soil.

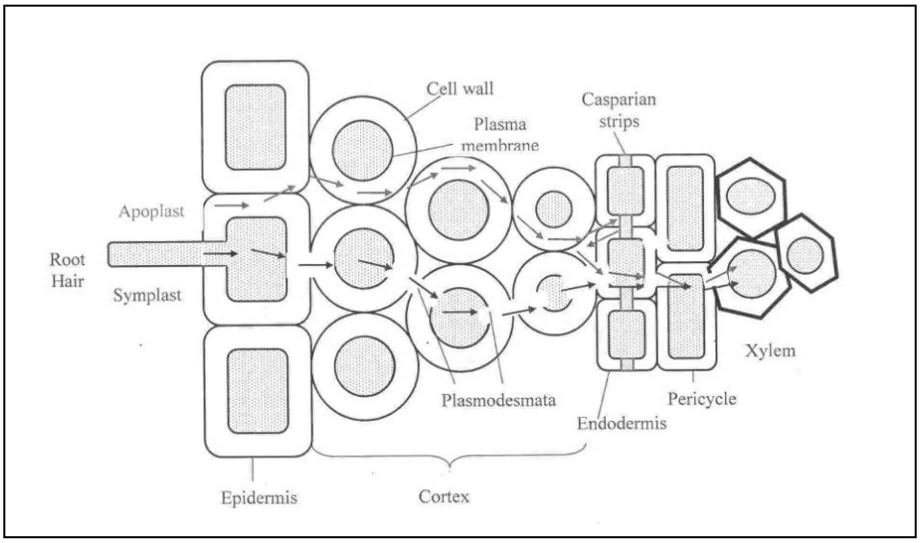
The Symplast Route

Symplast of a plant is the inner side of the plasma membrane which is used for transport of water and low molecular solutes from epidermis cells through the cortex into the endodermis, pericycle and after all into the xylem. The direct flow of small molecules such as sugars, amino acids and ions between cells is realized through the *plasmodesmata* – microscopic channels that traverse the cell walls of plant cells. A typical plant cell has over 10^3–10^5 plasmodesmata of approximately 50-60 nm in diameter.

Root Pressure

At night when the soil moisture is high or when process of transpiration is low by day, the stele's water potential is decreased due to the active transport of ions into xylem; that's why the water flows into the stele. The process of osmotic water uptake that realizes ascent of fluid to the xylem is accompanied with *root pressure*. This process is confirmed with such a phenomenon as *guttation* – the appearance of drops of xylem sap on the tips of leaves.

Root pressure can raise water only to about 20 meters; is not enough to push water to the top of the more tall plants.



]Long-Distance Transport in Plants

Xylem

A system that provides the supply of plant by water and mineral nutrients from the soil into upper parts of the plant is called *xylem* (from Greek $\xi\iota\lambda o\nu$ – wood). Water, inorganic ions and a number of organic chemicals are the main components of *xylem sap*.

Xylem consists of tracheids and lifeless wood vessels. The diameter of conductive elements of xylem is 10–500 μm; the length of conductive elements varies from hundreds micrometers to two meters. Because of the absence of cell shells and protoplasts the resistance of these elements is rather small to pass the water and solutes

The transport of substance by xylem is *unidirectional* (up only, from the roots to leaves). Maximal flow rate is about 15 m/h.

Mechanisms of Xylem Transport

Xylem sap travel by root pressure of *transpiration-cohesion-tension* mechanism.

Cohesion is the attractive force between molecules of the same substances. Water has an unusually high cohesive force again due to the 4 hydrogen bonds each water molecule potentially has with any other water molecule.

Adhesion is the attractive force between water molecules and other substances. Because both water and cellulose are polar

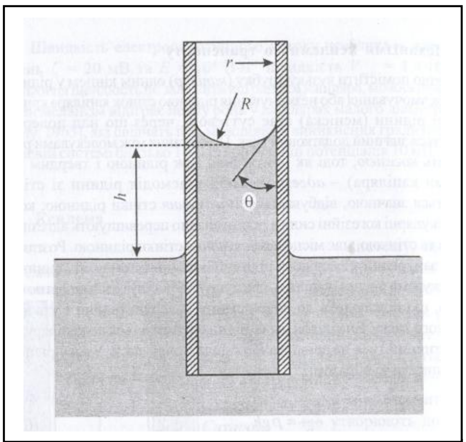
Tension can be thought as a stress placed on an object by a pulling force. This pulling force is created by the surface tension which develops in the leaf's air space. As water molecules leave the surface film by evaporating into the air spaces the remaining film forms menisci which become more and more concave and negative pressure increases. A meniscus has a tension that is inversely proportional to the radius of curvature of water surface.

A phenomenon caused by the surface tension at the interface of two nonmixing media is called *capillarity* and is observed when a distorted surface of a liquid leads to an elevation or depression of the liquid when in contact with a solid. When the liquid-gas interface is curved, the resultant surface tension produces an additional pressure difference across the interface. For a hemispherical liquid-gas interface having radius of curvature *R*, the pressure difference is given by the *Laplace equation*:

$$\Delta p = \pm\frac{2\cdot\sigma}{R} \qquad (9.10)$$

where σ is coefficient of surface tension of the liquid.

The sign for Δp is positive for a concave interface and negative for a convex interface. A cylindrical tube with a small internal diameter is called a *capillary*. The behavior of liquid in capillary is strongly modulated by the *wettability* of the tube walls. If the walls are wettable, the water rises in the capillary. For example, with water in xylem vessels, the attraction between the water molecules and the wall is great, causing the liquid to rise.



Capillary rise of a liquid:
h – the extent of rise; θ – the contact angle R – the radius of surface curvature; r – the radius of capillary

To calculate the extent of capillary rise, the balance of two forces, gravity $\pi r^2\rho gh$ acting downward and surface tension $2\pi r\sigma\cos\theta$, must be determined. Since these forces are balanced, the extent of rise (h) is defined by equality of two forces ($\pi r^2\rho gh = 2\pi r\sigma\cos\theta$), which leads to:

$$h = \frac{2\sigma\cos\theta}{\rho gr} \quad (9.11)$$

where ρ is the density of liquid, θ – the contact angle, g – the gravitational acceleration, $r = R\cos\theta$ – the radius of capillary and R – the radius of surface curvature.

A combination of adhesion, cohesion, and surface tension allow water to climb the walls of small diameter tubes like xylem. This is called *capillary action*.

Let's discuss as example a xylem vessel of typical radius 20 μm; using equation 6, we can determine that water (the density at 20 ^{0}C is 998.2 kg/m^3, surface tension is 0.0728 N/m) will rise to the following height:

$$h = \frac{2\sigma\cos\theta}{\rho gr} = \frac{2\cdot 72.8\cdot 10^{-3} N\cdot m^{-1}\cos 90^0}{998.2 kg\cdot m^{-3}\cdot 9.8 m\cdot s^{-2}\cdot 20\cdot 10^{-6} m} = \frac{1.49\cdot 10^{-5} m^2}{20\cdot 10^{-6}(m)} = 0.745 \text{ m}$$

Such a capillary rise would be sufficient to account for the upward movement of water in small plants only (≤ 1 m in height).

Long-distant transport in the plants is realized due to the *bulk flow* – the movement of a fluid driven by pressure gradient. Fluid movement in the xylem can be described quantitatively by *Hagen-Poiseuille's Law of Flow*: *volume (Q) of liquid flowing through a tube of length l is directly proportional to the pressure difference (p_1 - p_2) driving the liquid, and proportional to the fourth power of the tube radius (R).*

$$J_в = \frac{dV}{dt} = \left(\frac{\pi r^4}{8\eta l}\right)\Delta p, \quad (9.12)$$

or in generalized form:

$$J_V = L_V\Delta p, \quad (9.13)$$

where V is a volume of the liquid poured (cubic meters); t is the time (seconds); R is the internal radius of the tube (meters); Δp is the pressure difference between the two ends (pascals); η is the dynamic fluid viscosity (Pa·s); L is the total length of the tube in the x direction (meters).

Quantitative estimations [Nobel, 2005] for typical parameters of fluid flow in the xylem ($J_V = 10^{-3}$ m/s; $\eta = 10^{-3}$ Pa·s; $R = 20$ μm) demonstrate that the pressure gradient in xylem (–2·10^4 MPa/m) is sufficient to overcome gravity (10^{-2} MPa/m) and cause upward flow in the xylem vessels.

Phloem

The living tissue that carries organic nutrients (first of all sugar) along the plant is called *phloem* (from Greek word φλόος (*phloos*) – "bark"). Transport of organic products of photosynthesis through the phloem is called *translocation*. The specialised cells of the phloem such as sieve tubes participate in transport process. These cells arranged end to end to form long tubes with porous cross-walls between cells.

Phloem tissue consists of specialised conducting cells (*sieve elements*) which contains cytoplasm and are living in contrast to xylem conducting elements. Aqueous solution of organic products such as sugar (disaccharide sucrose) which is transported in phloem is called *phloem sap*. This sap consists of 30 % of dry matter, of which 89 % is sugar (sucrose and raffinose are most common).

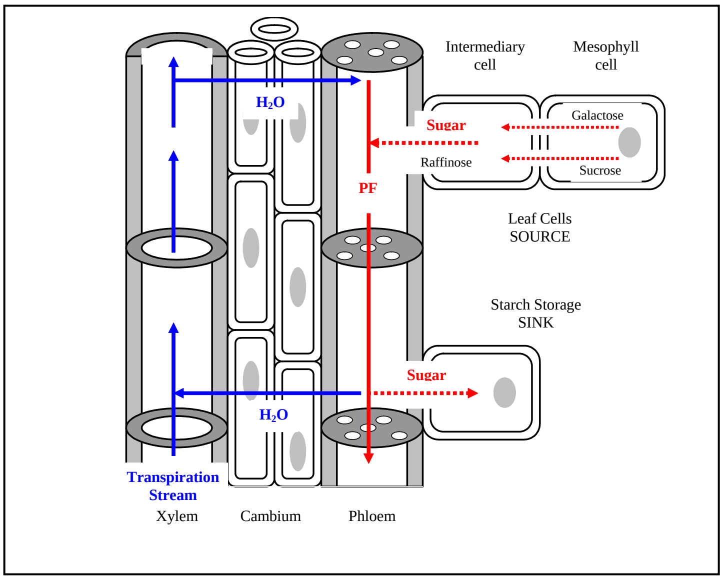
Mechanisms of Translocation

The process of transport of organic substances, first of all photoassimilates (photosynthetic products), in phloem is called *translocation*. E.Münch in 1930 proposed so-called the *pressure-flow hypothesis* which is based on assumption of the mass transfer of solutes from source to sink along a hydrostatic (turgor) pressure gradient.

The movement of phloem sap is bi-directional; phloem sap flows from source to sink with very small rate – about 1 m/hr. Sap is transported from a *sugar source* (a plant organ in which sugar is produced by photosynthesis or breakdown the starch) to a *sugar sink* (an organ in which sugar is consumed or accumulated). The sugars can be converted into starch which is insoluble and exerts no osmotic effect. That's why the osmotic pressure decreases at the sink. A storage organ such as a tuber or a bulb can play role of either a source or a sink, depending on the season.

The process of active transportation of solutes into the phloem from leaf mesophyll cells into sieve elements of the leaf veins is called *phloem loading*; transfer of solutes out of the sieve elements into sinks is called *phloem unloading*. Sieve tubes contain a lot of sugar, that's why they have a very negative osmotic potential. Water flows from xylem into the sieve tubes down its potential gradient, generating the a very high pressure potential (Ψ_p = 2-3 MPa): the sieve cells become very turgid.

At the same time, sugars are leaving the phloem in sinks, and water returns into xylem. This generates a low pressure potential in sinks. The pressure gradient is achieved along the sieve route from source to sink.



The main conclusion is that the principal mechanism of phloem transport is bulk flow that is driven by pressure gradient: high concentration of sugar and low level of water potential in the source induce the flow of water into the tube; removal the sugar from the sink increases water potential of this organ and causes water to flow out of the tube.

Measurement of Sap Flow

Sap is a fluid transported either in xylem cells such as tracheids and vessel elements or in phloem sieve tube elements of a plant. *Xylem sap* contains water with minerals while *phloem sap* consists of water with sugars that are transported from sources toward sinks.

Sap flow is measured in as liters of water per day. The process of measurement of sap flow is very important as makes it possible to estimate water balance of the plant and to calculate the total rate of water use of the plant (usually, the tree).

There are three principal methods of measurement the fluxes of water moving up the stem. All these methods are based on heating the transpiration stream with subsequent determination of the velocity of the heat pulse or the rate of propagation of heat along the stem.

Heat Pulse Method

This method was proposed at first in 1932 by B. Huber who used heat as a tracer of sap flow. This method provides the insertion of heat source into the narrow hole into the sap-wood of a tree; this source generates a pulse of heat of 1-2 seconds duration. Two other holes are drilled parallel the first one in the stem; a pair of temperature sensors are located in these holes. The lower temperature sensor registers the heat that propagates via conduction against the direction of transpiration stream while the upper sensor is responsible for registration of heat along the transpiration stream. Due to the directed transpiration stream both sensors will reach the same temperature at different instants of time. The time *t* taken for both sensors to achieve the same temperature gives an information about the velocity of the sap flow that is calculated as $\upsilon = d/t$, where *d* is the distance between the heater and temperature sensor. It is necessary to know additionally the cross-sectional area of the sapwood in the stem and the volumetric water content of the sapwood.

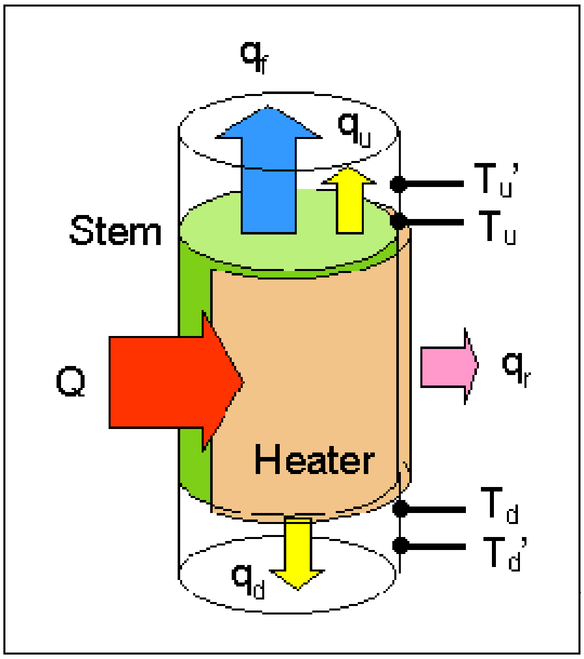
Thermal Heat Balance Method

The main idea of this method (Cermak et al., 1973; Sakuratani, 1981) is the application of a constant heat flux to a stem segment through an external annular heater and measurement of the temperature of the stem above and below the heated section. The sap flow *F* is determined by the following equation

$$F = (Q_h - Q_r - Q_u - Q_d - Q_s)/C_s \Delta T \,, \qquad (9.14)$$

where Q_h – heat input into the stem; Q_r – radial heat loss; Q_u – upward conducted heat; Q_d – downward conducted heat; Q_s – heat stored in the stem; C_s – heat capacity of the sap; ΔT – temperature difference between top and bottom of the heated section.

Heat balance fopr a stem segment to which heat flux Q is supplied. From T. Sakuratani. At: http://www.h6.dion.ne.jp/~sapflow/index.html

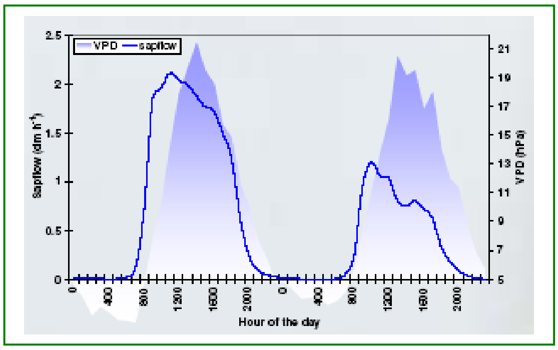


Heat Dissipation Method

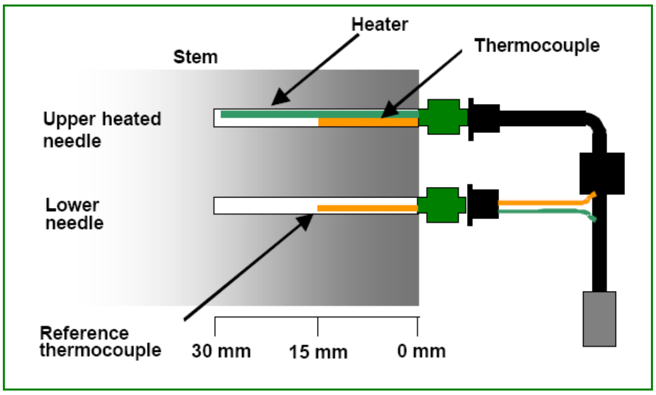
A method was proposed by A. Granier (1985) and is based on the insertion of two needles into the sapwood. Lower needle contains a source of constant heating and a thermocouple; the upper one contains only a thermocouple. Sap flow F is estimated due to the following equation

$$F = 0.428 S_a [(T_m - T_d)/T_d]^{1.231}, \qquad (9.15)$$

where S_a – sapwood area at probe height; T_m – maximum temperature difference obtained at night when sap flow is zero; T_d – actual temperature difference by day during measurement.



Larch sap flow during wet and dry day . After V. Carraro and T. Anfodillo, at: http://www.tesaf.unipd.it/people/Carraro/Xylem%20Sap%20Flow.pdf



Schematic represantationof a thermal dissipation probe (TDP30, Dynamax Inc, Houston, Texas, USA). From: http://users.ugent.be/~rsamson/phd/chapter31.PDF

Granier sensors are cheap, robust and reliable. It is possible to construct these sensors in laboratory conditions.

Practical Applications

The sap flow technique is the most promising for investigating forest water use at both temporal and spatial scales. For example, forest cover 64 % of the total land area of Japan. Because most of these forest areas are situated in mountain regions that serve as water supply catchment areas, quantitative estimation of the water use is important for water resource management of Japan.

The group of Japan scientists [Kumagai et al., 2007] has determined the amount of information needed to estimate watershed-scale transpiration in a Japanese cedar (*Cryptomeria japonica* D. Don) forest from sap flow measurements of individual trees.

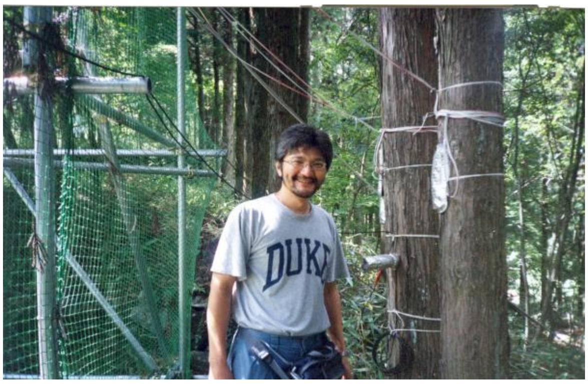
The measurements were made in two stand plots, an upper slope plot *UP* and a lower slope plot *LP*. The value of F_d was measured by the thermal dissipation method with Granier-type sensors. Each sensor consisted of a pair of probes 20 mm long and 2 mm in diameter; these probes were inserted in the sapwood about 0.15 m apart. The upper probe included a heater that was supplied with 0.2 W constant POWER. The temperature difference between the upper heated probe and the lower unheated probe was measured and converted to F_d according to Granier (1987).

The measurement of stand transpiration included estimation of the total sapwood area of the stand $A_{S\text{-}stand}$ and tree sapwood area $A_{S\text{-}tree}$; mean stand sap flux density J_S from tree-level measurements of xylem sap flux density F_d and calculation of stand transpiration E using the following equation

$$E = J_S \frac{A_{S-stand}}{A_G}, \qquad (9.16)$$

where A_G is the ground area.

Thus, variations in $A_{S\text{-}stand}$ and J_S were measured in an upper slope and a lower slope plot. It was found that the values of J_S in *UP* and *LP* were similar during the study period despite significant variations in environmental factors while $A_{S\text{-}stand}$ and $A_{S\text{-}tree}$ are major determinants of water use in a forest watershed.



Dr. Tomo'omi KUMAGAI near tree stem with Granier Sensors in Shiiba Research Forest, Kyushu University, Japan

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10. MASS TRANSFER: PARTICLES

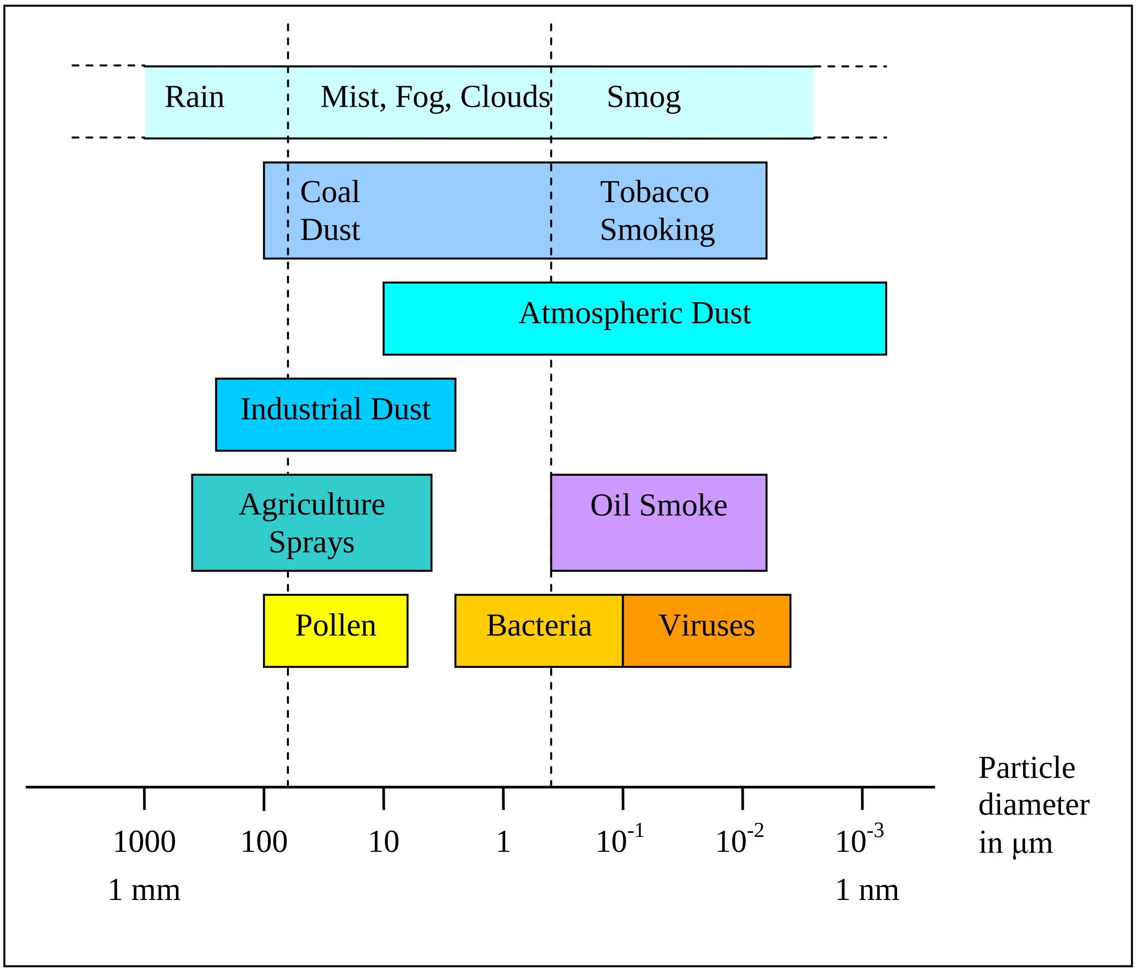
Airborne Particles

Any distinct (i.e., particulate) portions of solid, liquid, or gaseous matter larger than a single small molecule (larger than 1 nanometer in diameter) that are distributed in the air are called *airborne particles*.

Air Pollutants are substances of atmosphere that affect the health of humans, animals, plants and microorganisms.

Typical range of these particle size is given in Table 10.1. The size of atmospheric particles ranges from a few nanometers to several micrometers.

10.1.Typical range of the particle size



Sources of Atmospheric Particles

The principal anthropogenic air pollutants are emitted from industrial (transportation, fuel combustion, industrial processes, solid waste disposal), domestic (cooking, cleaning, gardening, painting, washing), commercial, agricultural and natural sources. As result the various particles appear in the atmosphere such as dust, soot, biomass burning, oil smoke, agricultural sprays, tobacco smoking, atmospheric gaseous pollutants, volatile organic compounds; the natural sources include windblown dust, forest fires, products of volcanoes eruption (sulphate, carbonate), biogenic gases (organic carbons) and volatile organic compounds, sea spray (*Na*, *Cl*, *Br*, sulphate).

Let's discuss the most hazardous for human health phenomena which are related with atmospheric particles.

Smog

Smog a term that starts with the start of one word *smoke* and ends with the end of another *fog*; is a form of air pollution produced as result of interaction of solar short-wave irradiation with hydrocarbons and nitrogen oxides and consequent photochemical reactions that lead to formation of ozone. Modern photochemical smog is come from vehicular and industrial emissions that have been released into the atmosphere. The history of smog is related with London, Great Britain, Los Angeles and San Francisco, the United States, Toronto, Canada, Tokyo, Japan, where an industrial development provoked periodical smog episodes that have had considerable health effects.

For example, the Los Angeles smog during the 1940s was induced by emissions of sulphur dioxide, particles, and nitrogen dioxide into the air; these pollutants caused the irritation of the eyes, nose, and throat. In addition, this smog was accompanied with significant decrease of air visibility.

The Los Angeles Smog
From: http://pdphoto.org/PictureDetail.php?pg=5215

Dutch chemist Arie Jan Haagen-Smit (1900–1977) postulated that the Los Angeles smog was induced in the atmosphere by series of photochemical reactions such as:

$$2NO + O_2 \rightarrow 2NO; \qquad (10.1)$$

$$NO_2 + h\nu \rightarrow NO + O; \qquad (10.2)$$

$$O + O_2 \rightarrow O_3. \qquad (10.3)$$

The automobile exhaust gases are one of the most significant sources of pollutants provoking the formation of photochemical smog.

Volatile Organic Compounds

Indoor Air include inorganic pollutants (carbon dioxide, carbon monoxide, nitrogen dioxide, sulphur dioxide, ozone), organic pollutants (volatile organic compounds, formaldegide, pesticides, polynuclear aromatic hydrocarbons, polychlorinated biphenyls), physical pollutants (particulate matter, asbestos, man-made mineral fibres, radon), environmental tobacco smoke, combustion-generated, microbial and biological contaminants, radioactive pollutants.

The fact is that the population of industrialized countries spend more than 90 percent of their time indoors. According to the World Health Organization, indoor air pollution is responsible for more than 1.6 million annual deaths and 2.7 % of the global burden of disease.

One of the hazardous pollutants of the indoor air are *Volatile Organic Compounds (VOCs)* – the gases that are emitted from certain solids or liquids and include a variety of chemicals hazardous for human health. The term “volatile” related to the tendency of these compounds to vaporize at normal temperature and pressure because of their low boiling points. These compounds have enough vapour pressures under normal conditions to significantly vaporize and enter the atmosphere.

The list of potential sources of indoor pollution includes paint, plastic, gas cooker, domestic mechanisms and machines, paper, textile, carpets, flooring and wall materials, animal dander and mites, mould, building materials, furniture, ventilation systems etc.

The most potential effects of VOCs are irritation of eyes and respiratory tract, narcotic action and depression of the central nervous system. Many of VOCs are known as human or animal carcinogens. The other health effects are related with the affect of heart, kidney and liver. It is known that inadequate indoor air quality can result in “multiple chemical sensitivity”, “new house syndrome”, and “sick building syndrome” and a cross-section of physical symptoms for those exposed such as allergies, frequent fatigue, asthma, headache, a feeling of uneasiness.

Tobacco smoking is especially dangerous for human health: it contains about 4,700 chemicals including nicotine, tar, polycyclic aromatic hydrocarbons, vinyl chloride, phenols, and cadmium. Gaseous phase of tobacco smoke consists of carbon monoxide, carbon dioxide, nitrogen oxides, ammonia, volatile nitrosamines, hydrogen cyanide, volatile sulfur containing compounds, volatile hydrocarbons, alcohols and aldehydes and ketones. Particulate phase mountains mainly nicotine, moisture and tar − the compound in tobacco that remains after the moisture and nicotine are subtracted.

Nicotine is an alkaloid that constitutes approximately 0.6-3.0% of dry weight of tobacco. Nicotine enters the brain during smoking within 15 seconds and remains there at high concentration during 2 hours. In low concentrations nicotine induces stimulating effect and state of euphoria.

Tar is purportedly the most destructive component in habitual tobacco smoking, accumulating in the smoker's lungs over time and damaging them through various biochemical and mechanical processes.

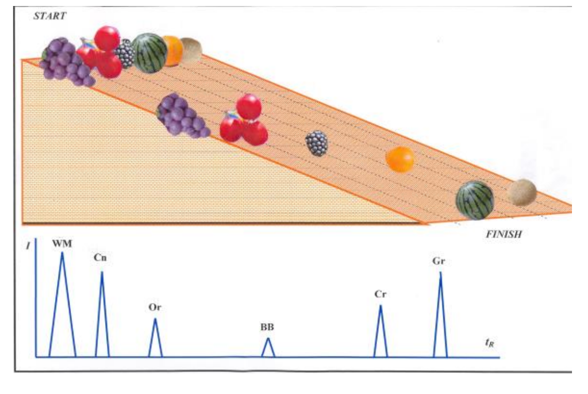
Methods of VOCs Analysis. All the methods of VOCs analysis consist of such principal stages: 1) sampling (sample trapping from the air and collection); 2) sample preconcentration and enriching; 3) removal of VOCs from air sample to the analytical device; 4) detection and identification of VOCs.

A sorbent is a material used to adsorb VOCs. Preliminary sample enriching permits to achieve the required sensitivity and selectivity of the analytical device. The most preferable method for enriching VOCs is application of *solid sorbents*. There are three main types of solid sorbents such as *inorganic sorbents*, *porous materials* based on carbon, and *organic polymers*.

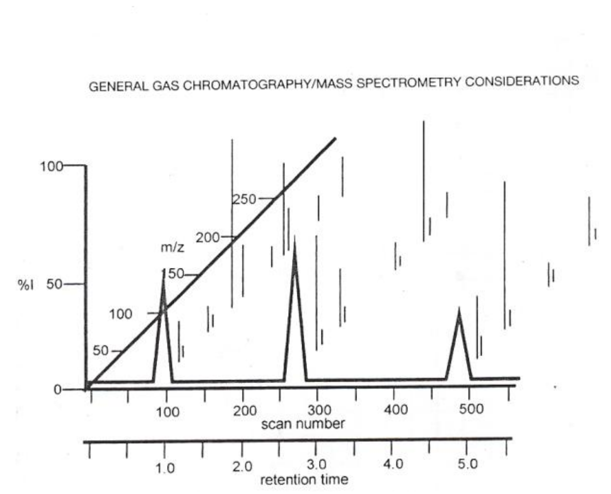
The principal ways to remove the sample from the sorbent are thermal desorption and solvent extraction. *Thermal desorption* means utilization of heat to increase the volatility of compound that is analyzed and to transfer it from the sorbent to analytical device. *Solvent extraction* is a methods that makes it possible to separate compounds on the basis of their different solubilities in water and organic solvent.

The principal method of VOCs analysis includes *Gas Chromatography (GC)* – analytical techniques that is based on vaporization of the sample and separation of mixtures due to passing a mixture dissolved in a mobile phase through a stationary phase; each component of the mixture can be presented as spectral peak in the chromatogram spectrum, and *Mass Spectrometry(MS)* – an analytical technique that measures the mass-to-charge ratio of charged particles that are accelerated by the electric field and are separated according to their masses and charges in a magnetic field.

Gas Chromatography-Mass Spectrometry (GC/MS) is a combination of gas chromatography that separates different molecules in a mixture as the sample travels the length of the column; each molecule takes its proper the *retention time* t_R to come out of the gas chromatograph, and mass spectrometer which captures, ionizes, accelerates, deflects, and detects the ionized molecules separately and identifies different substances within a test sample.



Model that explains the principle of action of gas chromatograph - each molecule of different shape, structure and mass takes its proper the *retention time* t_R to come out of the gas chromatograph.



Three-dimensional plot of scan number (time) versus mass/charge (*m/z*) versus relative intensity (%).
After: Grob and Barry, 2004.

Bioaerosols

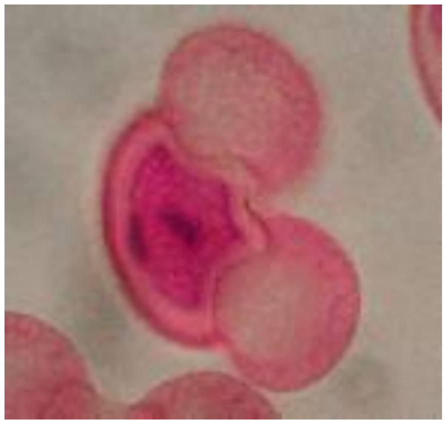
An *aerosol* is a colloidal suspension of a solid particles or liquid droplets in air.

A *bioaerosol* is defined as aerosol whose components contain, or have attached to them, one or more microorganisms.

A branch of biology that studies organic particles, such as bacteria, fungal spores, very small insects, pollen grains and viruses, which are passively transported by the air is called *aerobiology*.

The principal bioaerosols are: bacteria (*Legionella pneumophila*, *Micropolyspora faeni*, *Mycobacterium tuberculosis*, *Pseudomonas* spp., *Staphylococcus* spp., *Streptococcus* spp., *Bacillus* spp.) and bacterial products or components; fungi (prioncipally molds and yeasts) *Histoplasma capsulatum, Alternaria* spp., *Penicillum* spp., *Aspergillus fumigatus*, *Stachybotrys atra*, *Fusarium* spp., *Cladosporium* spp.; protozoa *Naegleria fowleri*, *Acanthamoeba* spp.; anthropods such as mites *Dermatophagoides farinae*, *D. pteronysssinus* and insects *Blatella germanica*, *Periplanetta Americana*, *Blatta orientalis*; animals (cats, dogs, ferret, guinea pigs, hamster, rabbit, rat, mouse), particularly dermal and urine antigens from pets or vermin; plants, especially pollen (*Betuta, Alnus, Pinus, Artemisia, Platanus, Ambrosia*).

Ivan Shishkin.
Pine.
1892. *Oil on canvas.*



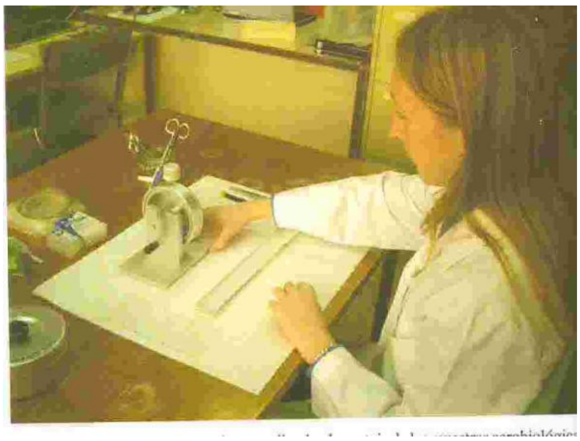
Pine (*Pinus pinea*)
pollen grains
(45-80 μm)

Pollen Samplers are intended for collection of airborne spores and pollen.

There are several types of bioaerosol sampling devices such as volumetric spore tapes, stationary jet-to-agar impactors, rotating media slit-to-agar impactors, centrifugal agar impaction samplers, liquid impingers, sedimentation samplers, whirling arm impactors.

Typical volumetric spore trap consists of a drum covered with an adhesive-coated transparent plastic tape. This drum rotates slowly during seven days. The analysis of tape under microscope and densitometer provides the information about qualitative and quantitative parameters of airborne particles and their dependence on the weatrher condition, time of day, season, etc.

Volumetric Spore Trap
(Burkard, Great Britain)



Analysis of airborne pollen collected with sampler.
From: M. del Mar Trigo Perez et al., 2007

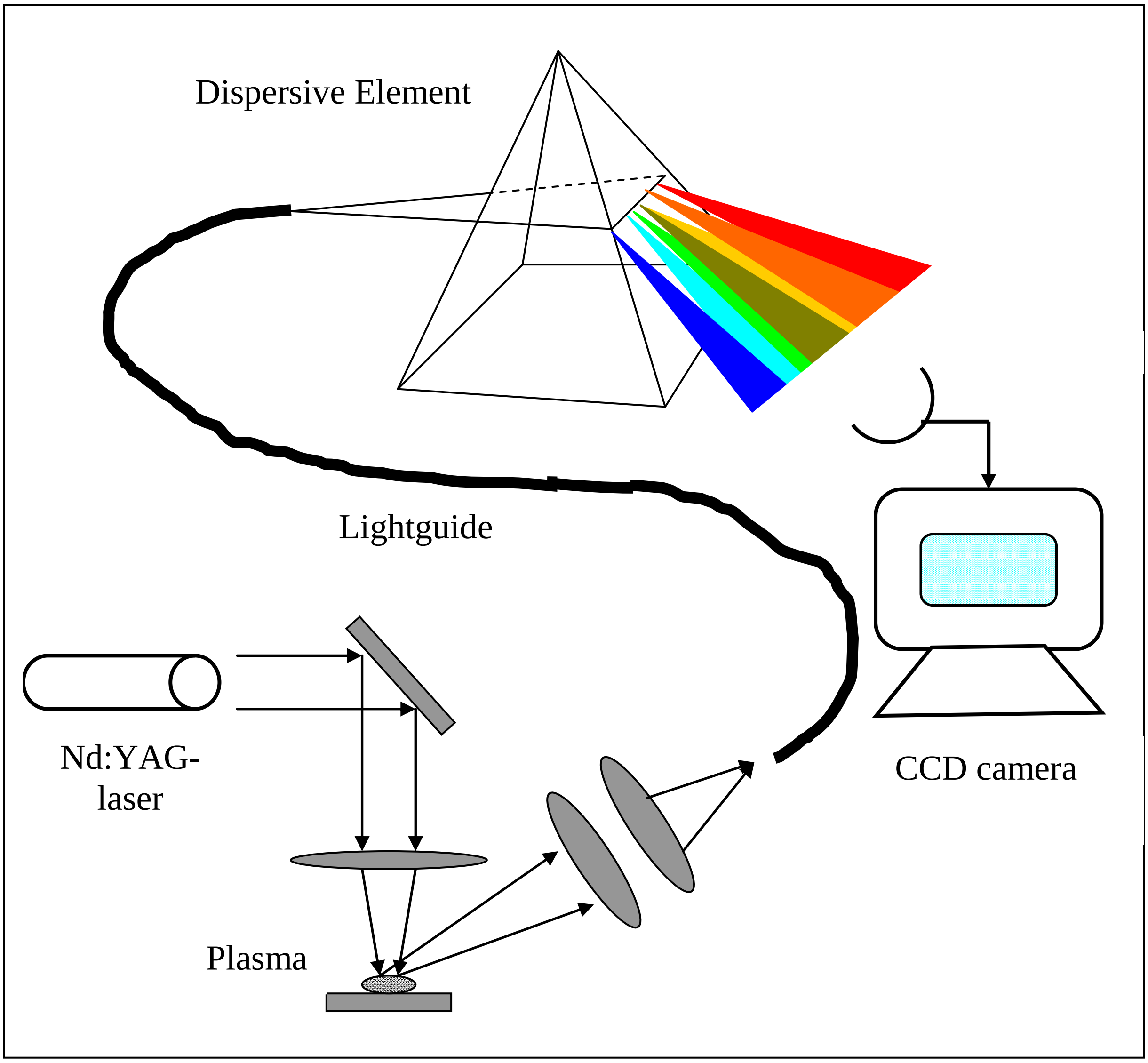
Bioaerosol Analysis. The following analytical methods are used to determine bioaerosols' parameters:

Laser light scattering depends on the refractive index and size of particle (the size range is 0.1 –100 μm); it is characterised by certain angular distribution of scattered radiation intensity: little particles demonstrate the symmetric distribution of scattered light, while large particles produce the presence a number of maxima and minima due to interference between the rays reflected from different points of the particle;

Laser diffractometry which is based on the deviation of laser radiation from the path predicted by geometric optics when this radiation interacts with a particle; it is used for measuring the size of particles and size distribution (the size range is 0.1 –1000 μm);

Laser Doppler techniques provides the information about particle velocity;

Laser-induced breakdown spectroscopy (*LIBS*) is a type of atomic emission spectroscopy which utilises a highly energetic laser pulse as the excitation source. LIBS can analyse any matter regardless of its physical state, be it solid, liquid or gas. Even slurries, aerosols, gels, and more can be readily investigated.



Laser-induced breakdown spectrometer

Airborne particles are characterized with different mass, size, and fate which determine the spatial distribution of the particles in the atmosphere and in the indoor air. The level of deposition of these particles depends strongly on their sizes: large particles (1-100 μm) deposit in the respiratory tract; smaller particles (10^{-2}-10 μm) can penetrate the tracheobronchial tubes leading to lungs and be deposited in the alveoli. Some particles are able to absorb gases dangerous for human health and enter either the respiratory or digestive systems, or bloodstream. Increased levels of fine particles in the air (for example, cigarette smoke particles smaller than 1 μm) provokes health hazards such as heart disease, altered lung function and lung cancer.

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11. MASS TRANSFER: WATER VAPOUR AND GASES

Higher plants transform sunlight to chemical energy by means of photosynthesis. A movement of gases, first of all, oxygen, carbon dioxide and water vapor, between a plant and atmosphere, is called *gas exchange*.

Transpiration

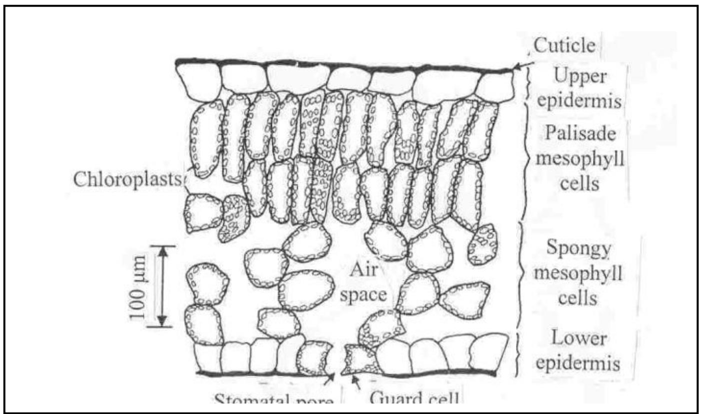
The process by which plants give off water vapour from their leaves to the atmosphere is called *transpiration*. This process provides the cooling the plant and mass flow of water and solutes due to pressure difference between upper parts of plant and its root system. The decrease of pressure in the leaf xylem occurs due to the diffusion of water out of stomata into atmosphere. Plants can lose tremendous amounts of water through transpiration in a day: for example, sunflower loses about 1-2 litres, while an oak – about 600 litres. About 90 % of water that enters via the root system into the plant is used for transpiration.

The process of transpiration depends on the leaf structure, particularly, on the multilayer hydrophobic wax cuticle, that exert resistance to diffusion of liquid water and water vapour and prevent the outer layer of the leaf from evaporation.

The level of evaporation and gas exchange is controlled by *stomata* (from Greek word *stoma (στόμα)*, plural *stomata*, that means "mouth") – small pores through cuticle and lower epidermis which are surrounded by a couple of guard cells. The change of the turgor pressure in the guard cells due to the uptake of potassium ions (K^+) inside the guard cells determines the opening or closing the stoma.

The process of transpiration consists of two stages – the evaporation of water from internal airspace of the leaf and the diffusion of water into the atmosphere.

Schematic cross-section of typical plant leaf



The Driving Force of Transpiration

The concentration of water molecules in a vapour phase can be expressed as *vapour density* – the vapour mass per unit volume (g/m^3). In addition, the concentration can be expressed in terms of *vapour pressure* (Pa or mm Hg). There is a relationship between vapour density *d* and vapour pressure *e*:

$$d_{sl}(T_l) = eM/RT, \qquad (11.1)$$

where M is molecular mass; R = 8,3143 J/mol·K – the gas constant; T – absolute temperature.

Molecules diffuse from a region of high concentration to a region of low concentration according to Fick's law of diffusion. As soon as the water vapour density is proportional to the vapour pressure (see Eq. (11.1)), water vapour will also diffuse down a vapour pressure gradient which occurs between the leaf air space of a leaf and the atmosphere that surrounds the leaf.

The fact is that the leaf air space is normally *saturated* with water vapour, while the surrounding atmosphere is usually unsaturated. That's why the gradient between the vapour pressure (concentration) in the internal and external regions of leaf air space appears. This gradient is driving force for transpiration:

$$J_m \approx C_{leaf} - C_{air} \approx e_{leaf} - e_{air}. \qquad (11.2)$$

Water vapour molecules encounter the certain resistance during diffusion through the leaf. It is necessary to remind leaf resistance R_{leaf} and R_{air} resistance which is created by boundary air layer. The transpiration equation may be transformed as follows:

$$J_m \approx \frac{e_{leaf} - e_{air}}{R_{leaf} + R_{air}}. \qquad (11.3)$$

The rate of transpiration (the rate at which water vapour escapes from a leaf) is:

$$E = \frac{d_{sl} - rd_{sa}}{R_l + R_a} = \frac{d_{sl} - hd_{sn}}{R_l + k_2\left(\frac{A^{0,3}B^{0,2}}{\upsilon^{0,5}}\right)}, \qquad (11.4)$$

where E is in units of kilograms per square meter per second; d_{sl} – the saturation density of water vapour in the leaf intercellular spaces (kg/m^3); d_{sa} – the saturation density of water vapour the outer air (kg/m^3); h – relative humidity of the air (relative units); A and B are the leaf dimensions (in the direction of air flow and at right angles to air flow correspondingly), and υ is the wind speed; k_2 = 200 s$^{1/2}$m^{-1}

So, mass flow in the plant is caused by the decrease of water pressure (formation of negative pressure) in the upper parts of the plant due to the diffusion of water from stomata to the atmosphere. This continual movement of water from the roots to the leaves is called the *Transpiration Stream.*

The main factors affecting the transpiration and gas exchange at whole are solar radiation, temperature, air humidity, carbon dioxide, atmospheric pollutants, wind, water supply, mineral nutrition, midday depression of net photosynthesis.

CO_2/O_2 Exchange

Energy metabolism of plants is realized due to the exchange of gases, such as carbon dioxide and oxygen. The main path of chemical reactions during photosynthesis is transfer of CO_2 and water into carbohydrates and oxygen

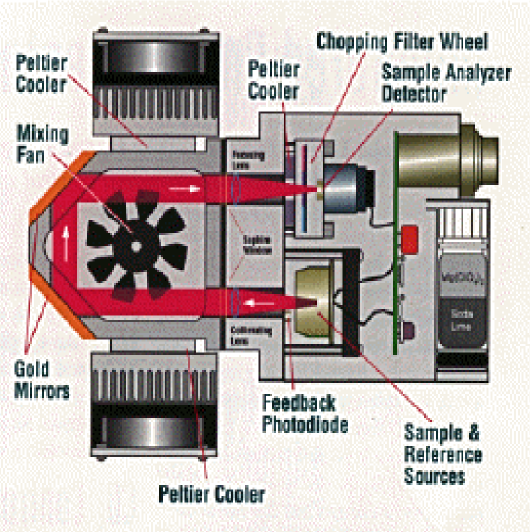
$$CO_2 + H_2O \xrightarrow{Light} [CH_2O] + O_2. \qquad (11.5)$$

Living cells of the plant participate in the gas exchange. But plants have not some kind of active mechanism for gas transport; they use diffusion only for moving gases. That's why the cells are located near the surface to shorten the distance for gases that must be travelled by them inside the leaf which are thin enough. The gases enter the leaf through stomata and then these gases diffuse through the air space inside the leaf. There is some compromise between processes of water lost by transpiration and the amount of carbon dioxide absorbed during photosynthesis. Plants must loose water in order to obtain carbon dioxide, but such a situation leads to dessication. That's why plants use large absorptive surface of the leaves together with spongy layer to protect leaves from dessication. The oxygen concentration in the sub-stomatal air space is increased under influence of light due to photosynthesis and carbon dioxide concentration is decreased. The stomata must be opened to compensate the lowering the intercellular CO_2. Bot opening stomata leads to intensification of transpiration. It was shown that the water potential gradient responsible for diffusion of water is considerably steeper than that for carbon dioxide; plants continuously mediate the compromise between the amount of carbon dioxide and the amount of water loss due to stomata regulating gas exchange.

Measurement of Gas Exchange

Gas Analyzers. Typical gas analyzers such as closed-path system (LI-7000, LI-COR) for measuring CO_2 flux and open-path system (LI-7500, LI-COR) for measuring H_2O flux are described in Chapter "Eddy Covariance". Here we shall consider LI-6400 System that utilizes gas exchange principles to measure the photosynthesis rates of plants. Net photosynthesis rates are expressed as rates of CO_2 uptake ($\mu molCO_2\ m^{-2}\ s^{-1}$). In the open-mode design of this device an air flow is moved through a controlled atmosphere surrounding a plant leaf in an assimilation chamber where the CO_2 level of the air is maintained steady-state.

The radiation of the infrared source radiation of LI-6400 System passes into the leaf chamber mixing volume and is twice reflected 90^0 by gold mirrors; then this radiation passes through a chopping filter wheel and reaches the detector The part of the infrared radiation is absorbed by the CO_2 in the sampling chamber. The chopping filter wheel is equipped with four CO_2 and water vapor filters that pass light in absorption and optical reference wavelengths for CO_2 and H_2O. These filters provide excellent rejection of IR radiation outside the wavelengths of interest, eliminating the effects of other IR absorbing gases.



LI-6400 chamber diagram

LI-6400 Chamber

Dr. Atsushi KUME provides measurements with LI-6400

Isotope Techniques. The main principles of this technmiques are described in Section "Isotopes in Precipitation". Here the fundamentals of stable isotope application for measurement of CO_2 assimilation are discussed.

The element carbon (*C*) exists as two stable isotopes (^{12}C, ^{13}C) and six radioactive isotopes (^{9}C, ^{10}C, ^{11}C, ^{14}C, ^{15}C, ^{16}C). Carbon-12 (^{12}C) contains 6 protons, 6 electrons, and 6 neutrons; carbon-13 (^{13}C) has 6 protons and electrons, but has 7 neutrons; and carbon-14 (^{14}C) also contains 6 protons and electrons, but has 8 neutrons. Other isotopes of carbon have too few or too many neutrons compared to protons causes these isotopes to be unstable.

The abundance of the stable isotopes of carbon are 98.89 % for ^{12}C and 1.11 % for ^{13}C. The table 11.1 shows the international standard and absolute isotope ratio for the carbon.

11.1. The international standard and absolute isotope ratio for the carbon

Element	***δ* value**	**Ratio Measured (*R*)**	**International Standard**	***R*, International Standard**
Carbon	$\delta\,^{13}C$	$^{13}C/^{12}C$	Vienna Pee Dee Belemnite (VPDB)	0.0112372

The standard is defined as 0‰. For carbon, the international standard is Pee Dee Belemnite (VPDB), a carbonate formation, whose generally accepted absolute ratio of $^{13}C/^{12}C$ is 0.0112372. Materials with ratios of $^{13}C/^{12}C$ > 0.00112372 have positive delta values, and those with ratios of $^{13}C/^{12}C$ < 0.00112372 have negative delta values.

Carbon Isotope Fractionation During Photosynthesis. If the isotope ratio $^{13}C/^{12}C$ is constant in atmosphere it can be decreased during photosynthesis due to a faster diffusion of ^{12}C through the stomata and walls of plant cells and fractionation for ^{12}C over ^{13}C due to the enzymatic processes. Usually, atmospheric CO_2 has a value $\delta\,^{13}C \sim -7\ ^0/_{00}$, while terrestrial plants are characterised with $\delta\,^{13}C \sim -24\text{-}34\ ^0/_{00}$, and desert plants – with $\delta\,^{13}C \sim -6\text{-}19\ ^0/_{00}$.

C_3 and C_4 plants have $\delta\,^{13}C$ values $-27\ ^0/_{00}$ and $-12\ ^0/_{00}$ correrspondingly. This isotope difference between C_3 and C_4 plants is related to the enzymatic carboxylation reactions during photosynthesis and can be used as criterium of belonging of plants to C_3 or C_4 types.

The isotope ratio of an element are changed by biochemical processes in the carbon cycle of the plant. The carbon cycle starts with the fixation of carbon dioxide. The extent of the isotope fractionation depends from the type of photosyntesis pathway.

In terrestrial plants, the principal source of variation in carbon-13 content is derived from the different photosynthetic pathways used for carbon dioxide fixation. Atmospheric CO_2 first moves through the stomata, dissolves into leaf water, and enters the outer layer of photosynthetic cells, the mesophyll cell. Mesophyll CO_2 is directrly converted by the enzyme Rubisco to a six-carbon molecule that is then cleaved into two molecules phosphoglycerate, each with *three* carbon atoms (such plants are called C_3 plants). Free exchange between external and mesophyll CO_2 makes the carbon fixation process less efficient, which causes the observed large ^{13}C-depletions of C_3 plants. The other plants incorporate CO_2 by the carboxylation of phosphoenolpyruvate (PEP) through the enzyme PEP carboxylase to make the molecule oxaoacetate which has *four* carbon atoms (such plants are called C_4 plants). To C_3 -plants belong sugar beets and grapes, C_4 -plants are tropical grasses, maize and cane. CAM-plants can use both ways to fix carbon dioxide, i.e. the pineapple.

The C_3 pathway results in a relatively large change in the carbon isotope proportions relative to atmospheric carbon dioxide. The C_4 pathway produces a much smaller change.

Application of Isotope Techniques

The physiological characteristics of the trees under the stress conditions such as air pollution, acid rains, dry deposition of gases and aerosols, wet deposition of rain and snow can be changed. The quantitative estimation of these changes can me made through measurement of such parameters as *net photosynthesis*, P_n, *stomatal conductance*, *gl*, and *intracellular* CO_2 *concentration*, C_i [Kume et. al., 2000]. These parameters were measured at a temperature 20 ^{0}C and at 1000 μ mol m^{-2} s^{-1} PFD with an open-flow infrared gas analyzer LI-6400.

During *photosynthetic* gas exchange, the plant takes up CO_2 and gives off O_2; whereas during *respiratory* gas exchange the direction of transport of the two gases is reversed. When more CO_2 is consumed in photosynthesis than is simultaneously produced in respiratory processes, the net uptake of CO_2 is *net photosynthesis* (Ph_n).

The stomatal aperture is the critical anatomical dimension for stomatal diffusion resistance. Its reciprocal, $1/r_s$, is the *stomatal conductance*, g_s, which is directly proportional to pore width. For mountain plants, for example, g_s ranges from 50 to 100 mmol m^{-2} s^{-1} for CO_2.

It was shown that these parameters were lower in the declined areas than in the non-declined areas ($P_n \approx$ 30 %, $gl \approx$ 50 %, and $C_i \approx$ 20 % lower, respectively).The authors explain the decreased value of P_n by stomatal restriction; small values of *gl* can be caused by insufficient water supply from the soil due to low water content and/or root development which would have prevented the stomata from opening fully [Kume et. al., 2000].

The ecophysiological effects of understory vegetation on an overstory *Pinus densiflora* were examined [Kume et al., 2003]: the unmanaged and managed, in which the understory vegetation was removed, stands were compared from the point of view of such a parameter of gas exchange as stomatal conductance *gl*. It was shown that the gl_{max} values of the managed stands were larger than those of the unmanaged stands: gl_{max} was about 25 μmol H_2O m^{-2} s^{-1} (30%) smaller than those in the managed sands. The smaller gl_{max} values in the unmanaged stands suggest that water for pine needles is more restricted in the unmanaged stands than in the managed stands.

The ecophysiological effects of understory vegetation on an overstory *Pinus densiflora* were examinated by Kume et al. (2003). The unmanaged and managed (in which the understory vegetation was removed) stands were compared from the point of view of long-term gas exchange. Particularly, needle carbon isotopic composition ($^{13}C/^{12}C$) was determined. In C_3 plants, leaf carbon isotopic composition is related to long-term water use [Farquhar et al., 1982]. Discrimination against ^{13}C during photosynthesis decreases with the increase of stomatal restriction.

The $^{13}C/^{12}C$ ratio reflects long-term leaf gas exchange characteristics and can be used as an index of water use efficiency. The results of investigations of Japanese colleagues confirm that water use efficiency was higher in the unmanaged stand than in the managed stands [Kume et al., 2003*a*]. The larger $\delta^{13}C$ values in the unmanaged stands suggest that water for pine needles is more restricted in the unmanaged stands than in the managed stands.

The traditional style of forest floor management in Japan has significant positive effects on the health conditions of *Pinus densiflora* plantations.

Carbon isotope discrimination in diverging growth forms of *Saxifraga oppositifolia* and in several types of phototrophs such as lichens, mosses, narrow-leaved grasses, perreials and shrubs was investigated in different successional stages in high Arctic glacier foreland [Kume et al., 2003*b*]. Two morphs of *S. oppositifolia*, the prostrate form (P-form) and the cushion form (C-form), which are distinguished with their shoot elongation characteristics, were compared through the estimation of $\delta^{13}C$ values. In all study sites, $\delta^{13}C$ of *S. oppositifolia* was distinctly different between two growth forms. At each site, $\delta^{13}C$ differed by about 2% between the two growth forms. The $\delta^{13}C$ values of the C-form were always more negative.

Investigation of isoptopic composition of the dominant vascular plants, mosses and lichens confirmed that the $\delta^{13}C$ value of the P-form was always the most positive among all species. This fact indicates severe physical restriction, including stomatal restriction, of CO_2 uptake in photosynthesis. The $\delta^{13}C$ values of the C-form also suggested the highest water use efficiency.The fact that the $\delta^{13}C$ values of the C-form of *S. oppositifolia* was always more negative than that of the P-form confirms that physical restriction in photosynthesis were small.

These results show that $\delta^{13}C$ depends on the growth form rather on the soil conditions.

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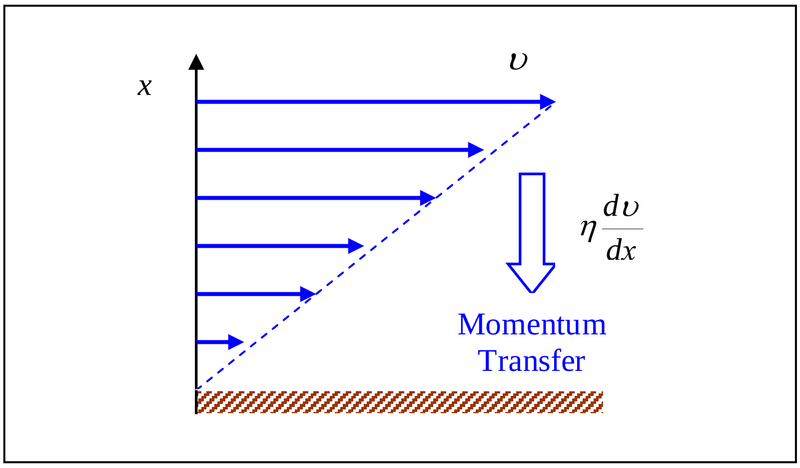
12. MOMENTUM TRANSFER

In classical mechanics, *momentum p* is the product of the mass *m* and velocity υ of an object. The air which is moving along the Earth surface consists of horizontal layers that provide vertical exchange with a velocity of movement due to the internal friction between the layers. This frictional force between adjacent layers of the air stream is called *viscosity*. Vertical exchange with a velocity induces corresponding exchange with a momentum, or *momentum transfer*. The movement of particles such as bioaerosols or rain droplets in the air is accompanied also with the momentum transfer. The objective of this chapter is to study the factors that affect the environmental momentum transfer.

Momentum Transfer in Laminar Flow

Laminar flow occurs when a gas or fluid flows in parallel layers, with no disruption between the layers. If these parallel layers are transferred with different moduli of velocity the friction force appears between them and momentum transfer occurs.



The process of momentum transfer is described with $J_p = \frac{dp}{Sdt}$; $L_p = -\eta$; $F_p = \frac{d\upsilon}{dx}$, where $\frac{dp}{Sdt}$ – momentum flux density; η – coefficient of internal friction (viscosity); S – area through which the momentum is transferred; $\frac{d\upsilon}{dx}$ – velocity gradient. This process is described by the *Newton's Law*:

$$J_p = L_p \cdot F_p \qquad (12.1)$$

or

$$J_p = \frac{dp}{Sdt} = -\eta \frac{d\upsilon}{dx}. \qquad (12.2)$$

The SI units of the momentum flux density is N/m^2; coefficient of internal friction – $N{\cdot}s/m^2$; velocity gradient – 1/s.

Momentum Transfer in Turbulent Flow

Turbulent flow is a gas or fluid regime characterized by chaotic motion. The theory of determination of wind profile in turbulent layer was developed by Prandtl (1920). He proposed the analogy between turbulent and molecular motion introducing *mixing length l* analogous to *mean free path* λ in the kinetic theory of gases.

It was considered a particle that arrived at level z of the boundary layer from lower level ($z - l$); the fluctuation of the horizontal component u of wind velocity is defined as follows

$$\delta u = u(z - l) - u(z) = -l\left(\frac{\partial u}{\partial z}\right). \quad (12.3)$$

These fluctuations of wind velocity in the horizontal direction are related to the vertical velocity fluctuations $\delta \upsilon$ which induces the vertical momentum flux:

$$F_m = \rho u (\delta \upsilon), \quad (12.4)$$

where ρ is the air density.

It was shown in Section "Eddy Covariance" that mean momentum of a large number of air particles is defined as

$$F = \rho (\overline{\delta u \delta \upsilon}) \quad (12.5)$$

where δu and $\delta \upsilon$ are fluctuations of the horizontal component u and vertical component υ of the wind velocity.

By combining the equations (12.3) and (12.5), we obtain

$$\rho (\overline{\delta u \delta \upsilon}) = -\rho \, \overline{l \delta \upsilon} \left(\frac{\partial u}{\partial z}\right).$$

Assumption that the velocity fluctuations are of the same order in all directions leads to

$$\delta \upsilon = -\rho u = l \left(\frac{\partial u}{\partial z}\right). \quad (12.6)$$

It is easy to obtain the value

$$\rho \delta u \delta \upsilon = -\rho l_m^2 \left(\frac{\partial u}{\partial z}\right)^2. \quad (12.7)$$

Supposing that fluctuations are proportional to the distance from the ground ($l_m = kz$, where $k = 0.4$ is von Karman constant) it is possible to obtain the differential equation for the vertical profile of wind velocity:

$$\left(\frac{\partial u}{\partial z}\right) = \frac{u^*}{kz}, \quad (12.8)$$

where u^* is a *friction velocity*; it is directly proportional to the wind velocity at height z and depends on the friction of the wind with the surface.

The integration of last equation leads to

$$u(z) = \frac{u^*}{0.4} \ln \frac{z}{z_0}, \quad (12.9)$$

where z_0 is called the *roughness parameter* of the surface.

When the surface is covered with a dense vegetation canopy the wind velocity profile is described as

$$u(z) = \frac{u^*}{0.4} \ln \frac{z - d}{z_0}, \qquad (12.10)$$

where d is the zero plane displacement which is determined by influence of drag and corresponding elevation of ground level.

Vertical Wind Profile near the Ground

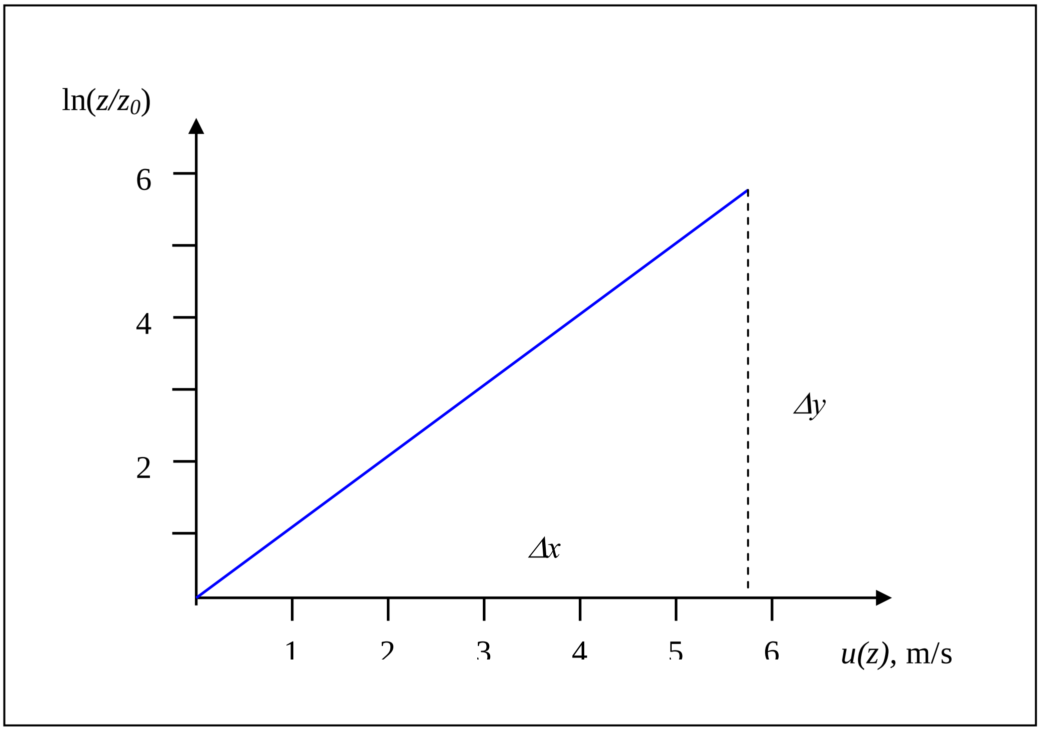
The equation (12.9) describes the logarithmic profile of wind velocity in a turbulent boundary layer.

Example: Let's calculate the values lnz, ln(z/z_0)**,** and $\upsilon(z)$ for u^* = 0.35 m/s and z_0 = 0.02 m.

Dependence lnz = $f[\upsilon(z)]$and ln(z/z_0) = $f[\upsilon(z)]$

z, м	lnz	z/z_0	ln(z/z_0)	u (z)= 0,875ln(z/z_0), м/с
6	1,79	300	5.7	4.99
4	1,39	200	5.3	4.64
3	1,10	150	5.0	4.38
2	0,69	100	4.6	4.03
1	0	50	3.9	3.41
0,5	–0,69	25	3.2	2.80
0,1	–2,3	5	1.6	1.40
0,05	–2,99	2.5	0.9	0.79
0,02	–4,61	1	0	0

The dependence lnz = $f[\upsilon(z)]$for bare soil is shown at the graph below:

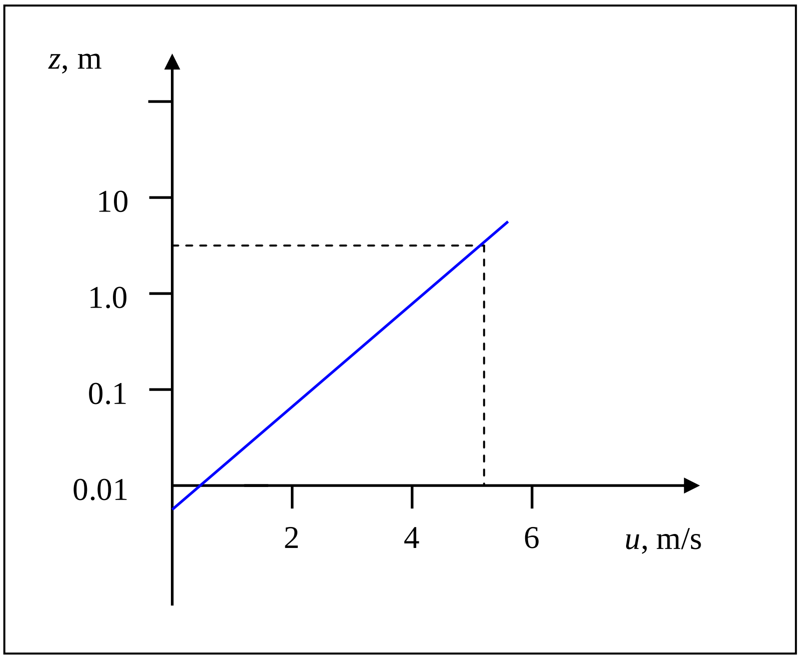


Value u^* can be found from the slope of the graph ln(z/z_m)= $f[u\upsilon(z)]$:

$\Delta y/\Delta x$= ln$(z/z_m)/u$ (z)= (5.7–0)/(4.99–0)=1.14 = 0,4/u^* .

Since u^* = 0,4/1.14 = 0,35 m/s.

Let's construct the dependence $z = f[u(z)]$:



Value z_0 can be determined from the dependence $\ln z = f[u(z)]$ as the point of interception of the graph with axis of ordinates where $u = 0$:

$$\ln z_0 = -5{,}3.$$

consequently $z_0 = e^{-5,3} = 0{,}005$.

Vertical Wind Profile over the Vegetation Canopy

Profile of wind velocity over the vegetation canopy is zero at the *displacement height* *d*, increases with height up to the constant value. This profile is described by the following equation

$$u(z) = \frac{u^*}{0.4}\ln\frac{z-d}{z_0}, \qquad (12.11)$$

where d – displacement height.

This equation is valid for $z \geq z_m - d$ only.

Example: Plot $\ln(z-d)$ as function of $u(z)$ for such parameters: the roughness parameters $z_0 = 0.2$ m; displacement height $d = 1.4$ m; friction velocity $u^* = 0.9$ m/s. Height z changes from 1.6 m to 6.0 m.

Using equation (2), we obtain $u(z)$, $z-d$, $\ln(z-d)$, and $\ln[(z-d)/z_m]$ for $h = 6$ m:

$$u(z) = \frac{u^*}{0.4}\ln\frac{z-d}{z_0} = \frac{0.9m/s}{0.4m/s}\ln\frac{6-1.4}{0.2} = 2.25\ln 23 = 2.25 \cdot 3.135 = 7.05 \text{ m/s}.$$

$z - d = 6 - 1.4 = 4.6$ m;

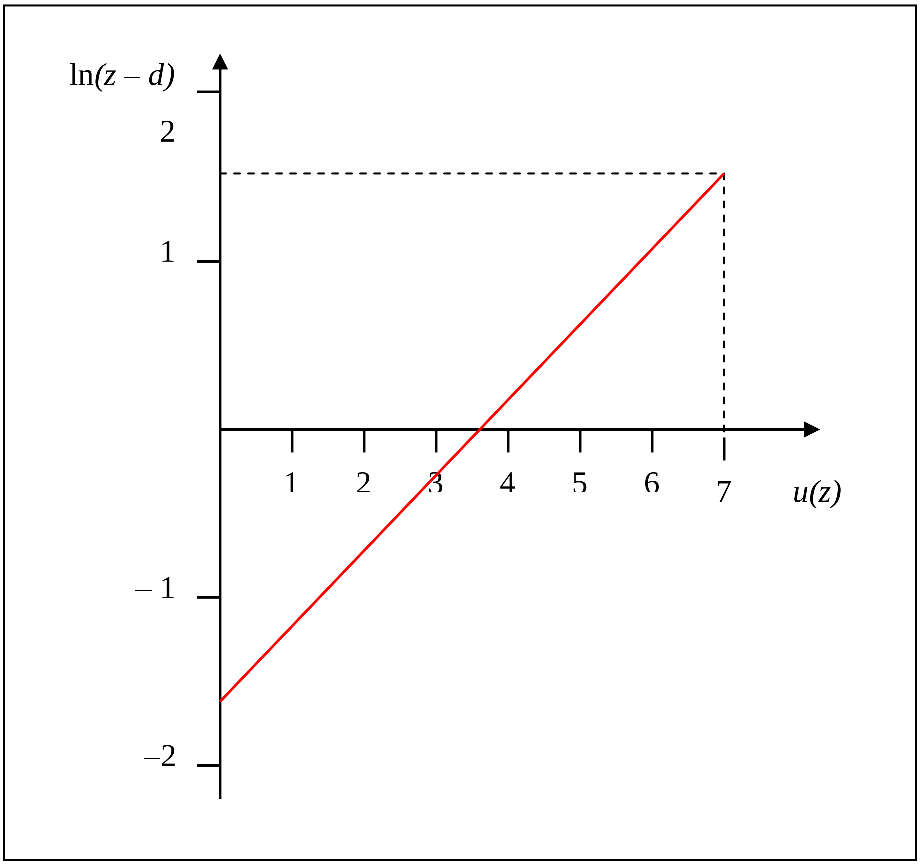
$\ln(z-d) = \ln 4.6 = 1.53$;

$\ln[(z-d)/z_m] = \ln(4.6/0.2) = 3.1$.

The similar calculations are performed for each value of height z = 4 m; 3 m; 2 m; 1,75 m; 1,6 m; the results are entered into the table.

z, m	$u(z)$	$z - d$, m	$\ln(z-d)$	$\ln[(z-d)/z_0]$
6	2.25·3.135 = 7.05	6 –1.4 = 4.6	ln4.6 = 1.53	ln(4.6/0.2) = 3.1
4	5.76	2.6	0.96	2.56
3	4.69	1.6	0.47	2.08
2	2.47	0.6	–0.51	1.1
1.75	1.26	0.35	–1.05	0.56
1.6	$x = 0$	0.2	–1.61	0

We plot the dependence of $\ln(z - d)$ on $u(z)$.



The value $u(z)$, that corresponds $\ln(z - d) = 0$ (interception of straight line $\ln(z - d) = f[\upsilon(z)]$ with abscissa axis:

$$u(z) = \frac{u^*}{0.4}\ln\frac{z-d}{z_0} = \frac{u^*}{0.4}[\ln(z-d) - \ln z_0] = \frac{0.9m/s}{0.4m/s}[0 - \ln 0.2] = 2.25 \cdot 1.609 =$$
$$= 3.62 \text{ m/s}.$$

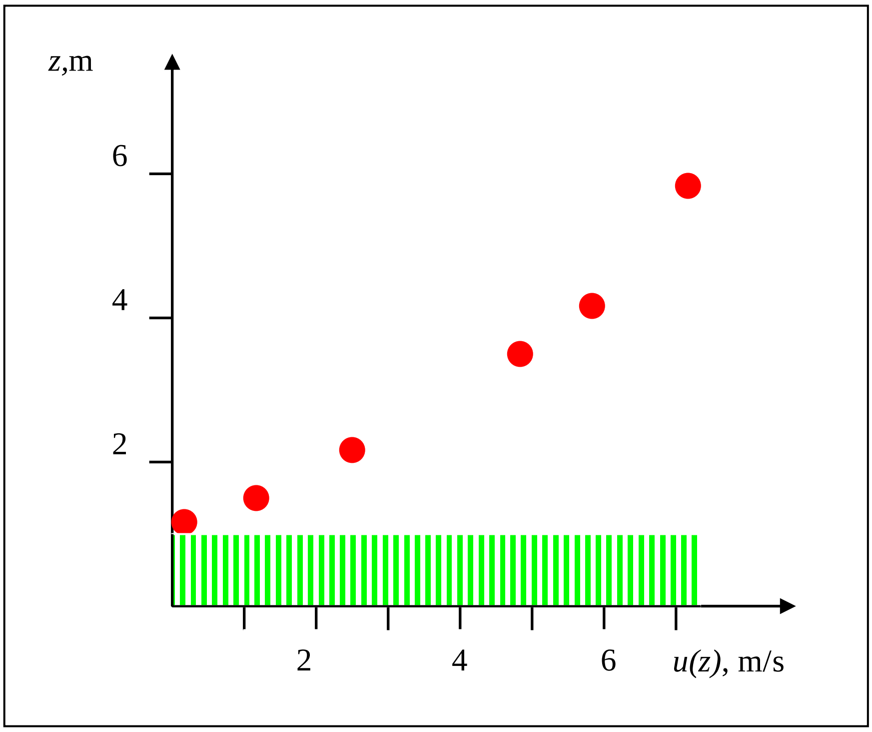
Value of $\ln(z - d)$, that corresponds $u(z) = 0$ is given as

$$0 = \frac{u^*}{0.4}\ln\frac{z-d}{z_0} = \frac{0.9m/s}{0.4m/s}[\ln(z-d) - \ln z_0] = 2.25[\ln(z-d) - \ln z_0].$$

so:

$$\ln(z - d) = \ln z_0 = \ln 0.2 = -1.6.$$

Thus, condition $z - d = z_m$ corresponds to $u(z) = 0$.
Graph below shows vertical wind profile over the vegetation canopy $z = f[\upsilon(z)]$.



Drag on Particles

The ratio of inertial to viscous forces is determined by the *Reynolds number Re*, which is defined as

$$Re = \frac{\upsilon \rho D}{\eta} = \upsilon D \nu , \qquad (12.12)$$

where η – dynamic viscosity of medium; ρ – density of medium; D – dimension of the system; ν – kinematic viscosity of medium. The transition from laminar to turbulent regime of flow is indicated by a critical Reynolds number (Re_{cr}), which depends on the exact flow configuration and is determined experimentally.

When Re is small ($Re < Re_{cr}$) viscosous forces dominate and the flow is laminar; when Re is large ($Re > Re_{cr}$), the inertial forces predominate and flow is turbulent.

Let's consider a situation of particle of radius R larger than the mean free path λ that is moving in laminar flow (Re is small or $Re = 2r\upsilon/\nu < 0{,}1$). In such a situation three forces are applied to the particle: gravity, buoyancy, and viscosity; the particle reaches a terminal velocity when the retarding forces, viscosity ($F_s = 6 \cdot \pi \cdot \eta \cdot R \cdot \upsilon$) and buoyancy ($\vec{F}_A = \rho_m \cdot V \cdot \vec{g} = \frac{4}{3} \cdot \pi \cdot R^3 \cdot \rho_m \cdot \vec{g}$), equal the weight ($m \cdot \vec{g} = \frac{4}{3} \cdot \pi R^3 \cdot \rho_p \cdot \vec{g}$) of the particle:

$$\frac{4}{3} \cdot \pi R^3 \cdot \rho_p \cdot \vec{g} = \frac{4}{3} \cdot \pi \cdot R^3 \cdot \rho_m \cdot \vec{g} + 6 \cdot \pi \cdot \eta \cdot R \cdot \upsilon , \qquad (12.13)$$

where m is the mass of particle, $R = \frac{D}{2}$ – the radius of particle, ρ_p and ρ_m – the density of the particle and medium, and η - the viscosity of the medium.

Hence:

$$\eta = \frac{2 \cdot g \cdot R^2 \cdot t \cdot (\rho_{sp} - \rho_m)}{9 \cdot l} \qquad (12.14)$$

and the terminal velocity (also called *sedimentation velocity*) can be determined as:

$$\upsilon_{sed} = g \cdot \frac{\rho_{sp} - \rho_m}{\eta} \cdot \frac{2 \cdot R^2}{9} . \qquad (12.15)$$

Let's consider a situation of particle of radius R larger than the mean free path λ that is moving in turbulent flow (Re is large or $Re = 2r\upsilon/\nu > 1$). Drag force opposing motion of particle is determined experimentally as

$$F_D = 0{,}5 c_D \cdot \rho \upsilon^2 \cdot A, \qquad (12.16)$$

where c_D – drag coefficient; A – cross-sectional area of the particle.
Balance of forces that act on particle is determined as

$$\frac{4}{3} \pi r^3 g(\rho - \rho_0) = 0{,}5 c_D \, \rho_0 \upsilon^2 \cdot \pi r^2 . \qquad (12.17)$$

For bioaerosols $\rho > \rho_0$, that's why the last equation can be rewritten as

$$\upsilon^2 = 8rg\rho / 3\rho_0 \, c_D . \qquad (12.18)$$

The sedimentation velocity of particle is given by

$$\upsilon_{sed} = 2g\rho r^2/9\rho_0 \nu. \quad (12.19)$$

The drag coefficient c_D is a function of Reynolds number *Re*:

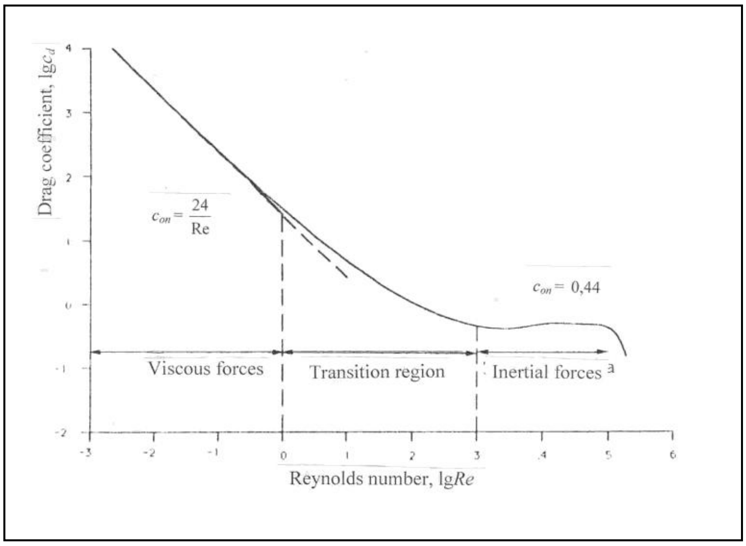
$$c_D = \frac{b}{\mathrm{Re}^n}, \quad (12.20)$$

where the values of b and n are given in the Table 12.1.

12.1. Values of b and n (Henry and Heinke, 1996)

Regime of flow	*Re*	*b*	*n*	Remarks
Laminar	<2	24	1	Friction drag predominates
Intermediate	2−500	18.5	0.6	Friction and form drag both important
Turbulent	500−2900,000	0.44	0	Form drag predominates

The dependence of the drag coefficient c_D on the Reynolds number *Re* is shown in figure;



Drag coefficient as a function of Reynolds number for spherical; particles. From Lichthart and Mohr, 1994.

For laminar regime the drag coefficient is defined as

$$c_D = \frac{24}{\mathrm{Re}}. \quad (12.21)$$

For turbulent regime the drag coefficient is proportional to υ^2 and to cross-sectional area A

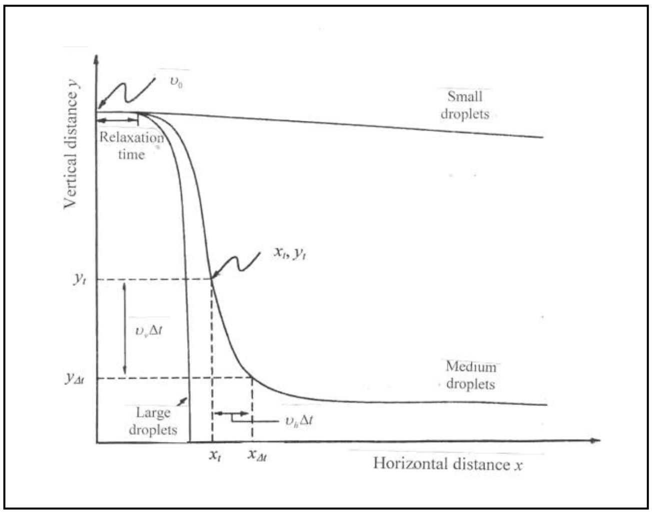
$$c_D = \rho\upsilon^2 \cdot A.$$

Trajectory of atmosphere is described by the following equation

$$\upsilon_t = \upsilon_f - (\upsilon_f - \upsilon_0)e^{-t/\tau}, \qquad (12.22)$$

where υ_t is the vertical or horizontal velocity of the particle at time t; υ_f is the final velocity;m υ_0 is the initial spray velocity for the horizontal axis and zero for the vertical axis; τ is the relaxation time which is a function of the particle size and density, atmospheric viscosity and density ($\tau = \rho_p D_p^2 C_c / 18\tau\ \eta$). Here C_c is the Cunningham slip correction factor that is determined from thwe tables [Lighthart and Mohr, 1994, Table 2.2].

Graph showing the trajectories for small, medium, and large particles is given below.



Graph showing idealized trajectories in a laminar flow atmospheric regime for small (< 6 μm), medium (6 μm < particle < 80 μm), and large (> 80 μm) particles at 50% RH and 20 ^{0}C (From: Lighthart and Mohr, 1994).

The fluctuations of wind velocity in the horizontal direction are related to the vertical velocity fluctuations which induces the vertical momentum transfer. This transfer depends on the wind velocity at height z and depends on the friction of the wind with the surface.

The movement of airborne particles is associated with the effect of frictional force between these particles and surrounding air which causes the change of velocity of movement of particles and corresponding momentum transfer. The value of frictional force depends on the size and density of particles, density and viscosity of the air.

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13. TRANSFER OF ELECTRIC CHARGES

Electrochemical Potential

Let's discuss a volume which is separated by a membrane into two KCl solutions of different concentrations. We assume that this membrane is permeable only to potassium ions K^+ but is impermeable to the larger Cl^- ions. The potassium ions will diffuse down their concentration gradient and transfer positive charge. As result a positive potential on the outside part of volume in comparison to the inside one and corresponding the potential difference $\Delta\varphi$ will be acquired across the membrane. This positive potential will oppose the movement of positive charges (potassium ions).

The work that has be done to move 1 mol of solute from the first compartment to the second one is given by:

$$\Delta W = RTln\frac{C_i}{C_e}, \qquad (13.1)$$

where R – the gas constant; T – the absolute temperature; C_i and C_e – the concentrations of potassium in the internal and external parts respectively.

The work that must be done to move 1 mol of ions against a potential difference $\Delta\varphi$ is:

$$\Delta W = zF\Delta\varphi, \qquad (13.2)$$

where z – the valency of ion; F – the Faraday's constant (a charge of one mole of electrons which is equal product of Avogadro's number and the elementary charge $F = N_a e = 6.022\cdot10^{23}\,\text{mol}^{-1}\cdot1.602\cdot10^{-19}\,\text{C} = 96485\,\text{C}$).

Thus, the concentration difference between two compartments presents the *concentration gradient*, which induces the diffusion flow of ions across membrane down their concentration gradient, while the accumulation of positive charges causes the appearance of the *electrical gradient* across the membrane which forces the potassium ions to move in opposite direction.

As a whole, the presence of both gradients makes for the state of electrochemical equilibrium of ions K^+. The electrical potential difference which corresponds to such a state is called *electrochemical potential*

Nernst Equation

At equilibrium the driving force on the ions due the concentration gradient will be exactly balanced by the driving force due to the potential difference:

$$nzF\Delta\varphi = RT\ln\frac{C_i}{C_e}. \qquad (13.3)$$

Solving for the potential difference gives so-called *Nernst Equation:*

$$\Delta\varphi = \frac{RT}{zF}RT\ln\frac{C_i}{C_e}. \qquad (13.4)$$

At $T = 20^0$C the factor $\frac{RT}{zF} = 58$ mV.

Intracellular and extracellular concentrations of ions in animal cells are given in Table 13.1.

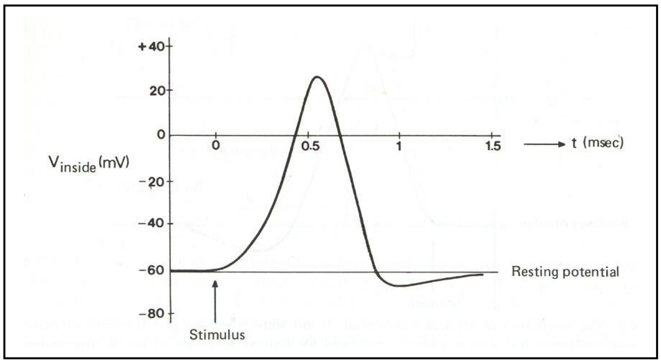
13.1. Intracellular and extracellular concentrations of ions

Concenration (mmol/L)	Gigantic axon of squid	Tailor's muscle of frog
Intracellular concentration C_i		
Na^+	78	13
K^+	392	138
Ca^{2+}	0.4	30
Mg^{2+}	11	16
Cl^-	104	2
Extracellular concentration C_o		
Na^+	462	108
K^+	22	2.5
Ca^{2+}	11	2
Mg^{2+}	56	1
Cl^-	286	

Membrane Potential

Internal and external media of the cell are characterized with non-uniform distribution of certain ions. For instance, the extracellular concentration of sodium ions is 5-15 times greater than the intracellular concentration. Potassium ions predominate in the intracellular medium; their concentration is 20-40 times greater than in the extracellular medium. In addition, cell membrane is characterized with selective ion permeability that is associated with appearance of ion channels. This membrane demonstrates in the resting state higher permeability for potassium ions, and lower one – for sodium ions.

That's why the *resting potential* is maintained across the membrane which has in most cells a negative value due to the excess negative charge insider compared to outside. Its value varies from – 60 to –90 mV.



A typical action potential.
After Sybesma, 1989.

Under the disturbance of the membrane by mechanical, chemical, or electrical stimulus its equilibrium state is upset and so-called *action potential* is appeared. It is located not over the entire membrane but at the place of disturbance; this action potential moves as a wave of electrical discharge along the membrane of a cell. For example, in the case of an elongated fiber, such as the axon of a nerve cell the action potential travels along the fiber at a constant rate like *nerve impulse*.

Long-Distant Communication in Plants

All the plant are characterized with such a common property as *excitability*. The external environmental factors affect the cells of higher plants and the excitation waves play role of information carriers during long-distant communications in plants. The responses to external stimuli are transmitted from cell to cell through plasmadesmata. The change in transmembrane potential creates a wave of depolarization (change of absolute value of a cell's membrane potential), or action potential. The velocity of propagation of action potential varies from 20-30 m/s for *Mimosa pudica* which close up and droop its leaves when touched, usually re-opening within minutes, to 60-170 m/s for *Dionaea muscipula* – a carnivorous plant that catches and digests animal prey such as insects and arachnids; the amplitude of action potential varies is about 20-30 mV.

Plants can response to various external factors such as solar radiation, extreme temperature, chemical treatment, mechanical wounding, activity of insects and herbivores; the bioelectrical impulses are generated by plants in response to such stimuli.

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14. HEAT TRANSFER

Heat transfer is the passage of thermal energy from a hot to a cold body (according to the second law of thermodynamics); it occurs through conduction, convection, radiation, or vaporization. A result of heat transfer is thermal equilibrium between the body and its surroundings.

Conduction

The transfer of energy within or through an object by fast particles or molecules, causing the ones next to them to move faster is called *conduction*. Molecules in high temperature materials have more kinetic energy than molecules in low temperature materials; these fast molecules collide causing neighboring molecules to move fast. Thus kinetic energy passes from the high temperature side of a material to the low temperature side. The conduction of heat occurs only if there is a difference in temperature between two parts of the conducting medium. Conduction takes place mainly in solids, where atoms are in constant contact. In liquids and gases, the particles are further apart, giving a lower chance of particles colliding and passing on thermal energy.

The process of heat transfer (thermal conductivity) is described by the *Fourier's Law*

$$J_q = \frac{dQ}{Adt} = -k\frac{dT}{dx}. \qquad (14.1)$$

or in generalized form:

$$J_q = L_q \cdot F_q \qquad (14.2)$$

where $J_q = \frac{dQ}{Adt}$ is heat flux density (quantity of heat that is transferred due to thermal conductivity during the time interval dt across the area A;); $L_q = -k$ is coefficient of thermal conductivity; $F_q = \frac{dT}{dx}$ – temperature gradient. The minus in this Fourier's equation denotes the fact that heat flows in the direction of decreasing temperature.

The SI units of the heat flux density of material is $J/m^2 \cdot s = W/m^2$; coefficient of thermal conductivity – W/m·K; temperature gradient – C/m.

Example. When a pig lies on concrete, the animal's belly and the concrete on which it lies are in contact. The temperature of the concrete's surface approximates that of the pig's belly surface. Assume that the 8-cm-thick concrete slab is on ground with a temperature of 0 °C, that belly-floor contact area is 3000 cm^2, the body temperature of pig is 38 °C, and the thermal conductivity of the concrete is 2.43 $W \cdot m^{-1} \cdot K^{-1}$.

Estimate the conductive heat transfer under steady-state conditions.

Solution. Conductive heat transfer flux from the belly to the concrete can be calculated as:

$$\frac{dQ}{dt} = -k \cdot A \cdot \frac{\Delta T}{\Delta x} =$$

$$= -2.43\frac{W}{m \cdot K} \cdot 3000 \cdot 10^{-4} m^2 (0-38)\ K / 8 \cdot 10^{-2}\ m =$$

$$= -2.43 \cdot 3 \cdot 10^{-1} \cdot (-38) / 8 \cdot 10^{-2} = 346.27\ J/s.$$

Try to estimate this situation if the pig will lie at the wood floor of the same thickness.

The values of the thermal conductivity k of various materials are given in Table 4.1 (Section "Temperature").

Convection

Heat transferred by the movement of a heated substance is said to have been transferred by *convection*. Convection occurs in two forms: natural and forced convection. In *natural convection*, fluid surrounding a heat source receives heat, becomes less dense and rises. The surrounding, cooler fluid then moves to replace it. This cooler fluid is then heated and the process continues, forming a convection current. *Forced convection*, by contrast, occurs when pumps, fans or other means are used to propel the fluid and create an artificial convection current.

Consider the convective heat exchange of objects with various shapes. The amount of heat J_C conducted across the boundary layer and convected away from the flat plate (e.g., the surface of a leaf per unit time and area) by forced convection is:

$$J_C = -2k_{air}\frac{(T_{leaf} - T_{air})}{\delta}, \qquad (14.3)$$

where k_{air} is the thermal conductivity coefficient of air, T_{leaf} the leaf temperature, and T_{air} the temperature of the air outside a boundary layer of thickness δ. This can be expressed as:

$$\delta(\text{mm}) = 4.0\sqrt{\frac{L(m)}{\upsilon(m/s)}} \qquad (14.\ 4)$$

where L is the mean length of the leaf, υ is the ambient wind speed, and the factor 4.0 has dimensions in $m/s^{1/2}$.

In the case of a cylinder (e.g., an animal), the heat flux density is:

$$J_C = -2k_{air}\frac{(T_{surf} - T_{air})}{r\ln(\frac{r+\delta}{r})} \qquad (14.5)$$

where r is the cylinder radius, T_{surf} surface temperature, and δ is calculated as:

$$\delta(\text{mm}) = 5.8\sqrt{\frac{D(m)}{\upsilon(m/s)}} \qquad (14.6)$$

where D is the cylinder diameter.

It is possible to use the following relation for objects of irregular shape which is known as *Newton's Llaw ofCcooling* which states that the rate of change of the temperature of an object is proportional to the difference between its own temperature and the ambient temperature (i.e. the temperature of its surroundings). It describes the rate of heat loss (J_C) in W/m^2 per unit surface area of a body in a cool air stream as:

$$J_C = k_c(T_{surf} - T_{air}), \qquad (14.7)$$

where $k_c = k_{air}/\delta$ is the *convection coefficient* with units $W{\cdot}m^{-2}{\cdot}K^{-1}$.

Example. Calculate the heat flux density conducted across the boundary layer and convected away from the surface of a sheep if the body of the animal approximates a cylinder with a radius of 60 cm, the surface temperature (T_{surf}) is 38 °C, the temperature of the air (T_{air}) is 20 °C, and the ambient wind speed (υ) is 80 cm/s.

Solution. The average of the boundary layer (δ) is:

$$\delta = 5.8 \cdot \sqrt{\frac{D}{\upsilon}} = 5.8 \cdot \sqrt{\frac{0.6}{0.8}} = 5 \text{ mm} = 5 \cdot 10^{-3} \text{ m} .$$

Using Equation (13.6) and k_{air} (0.0257 W·m^{-1}·K^{-1} at 20 °C), calculate the heat flux density conducted across the boundary layer.

$$J_C = -2k_{air}\frac{(T_{surf} - T_{air})}{r\ln(\frac{r+\delta}{r})} = \frac{0,0257 \cdot (38-20)}{0,3 \cdot \ln\left(\frac{0,3+0.005}{0.3}\right)} = 93 \text{ W/m}^2.$$

Radiation

Radiation is transfer of heat through electromagnetic radiation in the heat spectrum. Hot or cold, all objects radiate heat—unless they are at absolute zero, which is unattainable. No medium is necessary for radiation to occur; radiation works even in and through a perfect vacuum. A prime example of this is heat from the Sun, necessary for life on earth, which travels through the vacuum of space before warming the earth.

Thermal radiation is electromagnetic radiation emitted from the surface of an object which is due to the object's temperature. A *black body* is an ideal source of thermal radiation

Black-body radiation is described with the following relationships:

Wien Displacement Law states that there is an inverse relationship between the wavelength of the peak of the emission of a black body and its temperature

$$\lambda_{max} = \frac{b}{T}, \qquad (14.8)$$

where λ_{max} is the peak wavelength in meters; T is the temperature of the blackbody in kelvins (K), and b is a constant of proportionality, called *Wien's displacement constant* and equals 2.897 768 5(51)·10^{-3} m K.

Planck's Law describes the spectral radiance of electromagnetic radiation at all wavelengths from a black body at temperature *T*. As a function of wavelength λ, Planck's law is written as

$$I(\lambda,T) = \frac{2\pi hc^2}{\lambda^5(e^{hc/\lambda kT}-1)}, \qquad (14.9)$$

where h – Planck's constant (h = 6,626·10^{-34} Дж·с); λ – wavelength; c – speed of light; T – absolute temperature; k – Boltzmann's constant; e – base of the natural logarithm.

Stefan-Boltzmann's Law states that the total energy radiated per unit surface area of a black body in unit time (known as the black-body irradiance), I, is directly proportional to the fourth power of the black body's thermodynamic temperature T:

$$I = \sigma T^4, \qquad (14.10)$$

where R is the power radiated by the body (W); σ is Stefan–Boltzmann constant (σ = 5,67051·10^{-8} W·m^{-2}·K^{-4}).

In the case of a grey body, that doesn't absorb or emit the full amount of radiative flux this law is given as

$$I = \varepsilon\sigma T^4, \qquad (14.11)$$

where ε is a constant called the *emissivity*.

The total absolute power of energy radiated for an object is

$$P = IA = A\varepsilon\sigma T^4, \qquad (14.12)$$

where A is the surface area of the object (m).

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15. ENERGY BALANCE OF THE PHYSICAL AND BIOLOGIVCAL SYSTEMS WITH THE ENVIRONMENT

Global Energy Balance for the Earth-Atmosphere System

The Sun with its surface temperature 6000 K emits the shortwave radiation with wavelengths in the range 200-5000 nm and peak at about 500 nm. The incoming solar radiation is distributed in such a way: reflection from clouds (16 %), air molecules and aerosols (7 %), Earth's surface (8 %); absorption by ozone in the upper atmosphere and by clouds and water vapour in the lower atmosphere (20 %). The rest radiation reaches the Earth surface as direct or diffuse solar radiation (49 %).

Short-Wave Solar Radiation

The temperature of the Sun is 6000 K. The wavelength at which the peak of the emission occurs for the Sun is determined from *Wien's DisplacementLlaw*

$$\lambda_{max}T = 2.898\cdot10^{-3} \text{ m K}. \qquad (15.1)$$

Solving for λ_{max}, we have

$$\lambda_{max}(Sun) = (2.898\cdot10^{-3} \text{ m K})/6000 \text{ K} = 4.83\cdot10^{-7} \text{ m} = 483\cdot10^{-9} \text{ m} = 483 \text{ nm}.$$

The maximum of solar radiation is located in visible part of spectrum.

As solar radiation passes through the Earth's atmosphere, some of it is absorbed or scattered by atmosphere molecules and particles.

The solar radiation that passes through directly to the Earth's surface is called *Direct Solar Radiation* $E_S\downarrow$.. Here $E_S\downarrow = E_S\cos\theta$, where θ is the zenith angle.

The radiation that is scattered and reflected by the atmosphere molecules and particles is called *Diffuse Solar Radiation* $E_D\downarrow$.

The direct component of sunlight and the diffuse component of skylight falling together on a horizontal surface make up *Global Solar Radiation* $E_g\downarrow$.

Thus, the global solar radiation is defined as

$$E_g\downarrow = E_S\downarrow + E_D\downarrow = E_S\cos\theta + E_D\downarrow.. \qquad (15.2)$$

Atmospheric Radiation

Atmosphere emits longwave radiation; the major sources of this radiation are water vapour (5-7 μm and above 17 μm), carbon dioxide (near 4.5 μm and above 13.5 μm), and ozone (near 9.6 μm). As a whole, emission spectrum of atmosphere occupies the range 5-100 μm.

The *exitance* of the atmosphere is the power of light or energy radiation that is output, through reflection or radiation, from the atmosphere

$$M_A\uparrow = \sigma T_A^4, \qquad (15.3)$$

where T_A – absolute temperature. The SI units of the exitance are watts per square metre (W/m^2).

As soon as atmosphere is not an ideal black body but is a grey body which radiates a portion of radiative flux, characterized by its emissivity ε, its exitance is

$$M_A\uparrow = \varepsilon\sigma T_A^4, \qquad (15.4)$$

The atmospheric radiation is emitted towards the Earh's surface and into space.

If the sky occupies a whole hemisphere, the atmospheric exitance is equal to the atmospheric irradiance – radiant power incident per unit area upon Earth's surface

$$M_A\uparrow = E_A\downarrow .$$

Ozone Layer

Ozone and molecular oxygen absorb ultraviolet component of solar radiation and play significant role in radiation balance of the atmosphere. These processes lead to photochemical reactions that induce the increasing temperature of the stratosphere; in addition, spectral filtration and control of shortwave solar radiation is realized.

The main part of ozone (about 90 %) is located in the stratosphere between 10 and 50 km above the surface (so-called "ozone layer") with maximum at 20-25 km. These layer is able to absorb in spite of low concentration ultraviolet solar radiation such as UV-C (< 280 nm) and UV-B (315–280 nm) partially.

Shortwave (<270 nm) ultraviolet radiation is able to split molecules of oxygen into individual oxygen atoms O (atomic oxygen) which combines with unbroken O_2 to create ozone, O_3.

Solar radiation induces such processes in the stratosphere:

1. interaction of shortwave (λ< 240 nm) radiation with ozone molecule which leads to formation of atomic oxygen:

$$O_2 + h\nu \rightarrow O + O. \qquad (15.5)$$

2. interaction of atomic oxygen with molecular one:

$$O + O_2 + M \rightarrow O_3 + M, \qquad (15.6)$$

where the M represents any other molecule (usually, nitrogen or oxygen).

3. interaction of longwave (λ=300-315 nm) radiation with ozone that leads to its reverse transformation:

$$O_3 + h\nu \rightarrow O_2 + O. \qquad (15.7)$$

In addition, interaction of stratospheric chlorine, nitrogen, bromine, and hydrogen with ozone provokes the damage of it due to such reactions:

$$X + O_3 \rightarrow O_2 + XO; \qquad (15.8)$$

$$XO + O \rightarrow X + O_2, \qquad (15.9)$$

where X is chemical reagent.

In such a way, ozone layer plays role of an effective spectral filter for UV-B radiation which causes direct damage to vitally important molecules such as DNA and proteins.

Long-Wave Terrestrial Radiation

The Earth's surface acts as a blackbody with its own temperature of 288 K. Thus, this blackbody emits the longwave radiation with wavelengths in the range 4-50 μm and peak at about 10 μm. In fact, from Wien's dispacment law, we have:

$$\lambda_{max}(Earth) = (2{,}898\cdot10^{-3}\text{ m K})/288\text{ K} = 10\cdot10^{-6}\text{ m} = 10\ \mu\text{m}.$$

Greenhouse Effect

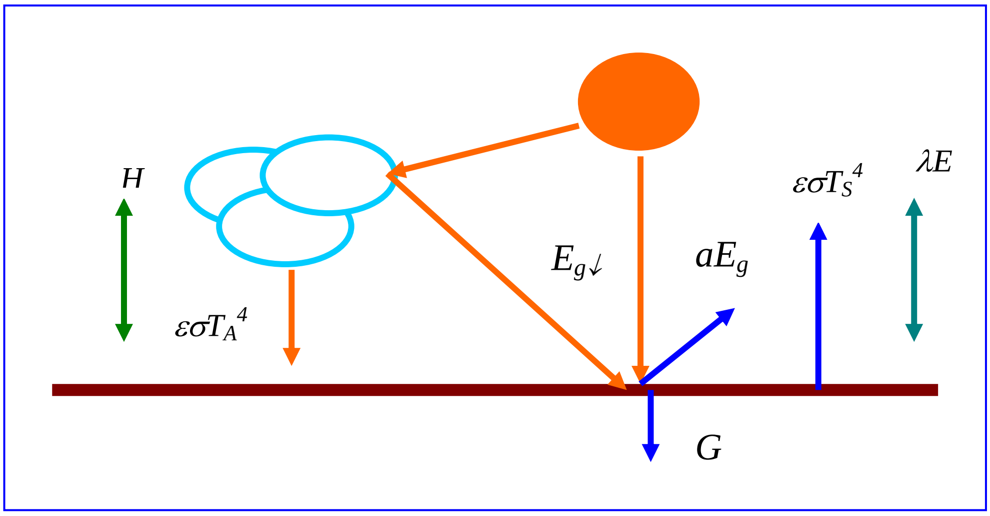
Human activity leads to increasing atmospheric gases such as CO_2, N_2O, CH_4, *CFCs*. The specific peculiarity of these gases is their ability to absorb optical radiation in infrared part of spectrum. The fact is that the Earth reflects about 30 % of incoming solar radiation, while 70 % of this radiation is absorbed warming the land. The infrared radiation of the Earth's surface is absorbed by the atmospheric gases and clouds and doesn't escape to space. The atmospheric gases usually have nonlinear molecular structure, possess electric dipole and absorb longwave radiation of the Earth. This warming of the lower atmosphere called the *greenhouse effect*. The thermal balance is destroyed and global temperature of the Earth is increasing due to the greenhouse effect. The global warming can induce the melting of mountain glaciers and transfer water from the land to the sea that will raise global sea level and provoke flooding large agricultural areas.

Energy Budget of the Terrestrial Surface.

Net radiation of is the sum of all the gains and losses of radiant power at the Earth's surface:

$$E_{net} = (1 - a)\, E_{g\downarrow} - \varepsilon\sigma(T_S^4 - T_A^4), \qquad (15.10)$$

where $E_{g\downarrow}$ is incoming short-wave solar radiation (W/m^2); $-a$ is albedo – the fraction of incident solar radiation reflected by a surface; thus, $-aE_{g\downarrow}$ is short-wave solar radiation reflected from the surface; $-\varepsilon\sigma T_S^4$ is upward long-wave terrestrial radiation, and $\varepsilon\sigma T_A^4$ is downward long-wave atmospheric radiation.



Balance Equation of the Terrestrial Surface

This net radiation is expended through various processes such as ground heat flux *G*, latent heat λE, sensible heat flux (or convective heating) *H*

$$R_{net} = G + \lambda E + H. \qquad (15.11)$$

Ground Heat Flux G (W/m^2) is the process where heat energy is transferred from the Earth's surface downwards via conduction. A temperature gradient must exist between the surface and the subsurface for heat transfer to occur. Heat is transferred downwards when the surface is warmer than the subsurface (positive ground heat flux). If the subsurface is warmer than the surface then heat is transferred upwards (negative ground heat flux). Ground heat flux can be presented by the amount of heat transmitted per unit of area per unit of time. Ground heat flux is usually negligible in temperate and tropical ecosystems, while it compose about 10-20 % of net radiation in arctic regions.

Latent Heat Flux λE is the amount of energy in the form of heat that is required for a material to undergo the change of phase. For example, the phase change of a liquid to a gas is called *evaporation*. The heat used in the phase change from a liquid to a gas is called the *latent heat of vaporization*. The energy exchange by evaporation is λE, where $\lambda = 2.43 \cdot 10^6$ J/kg is the latent heat of vaporization, and E is evaporation or transpiration rate, kg/m^2·s. When evaporation is taking place we say there is a *positive latent heat flux* (transfer). Latent heat flux is the energy transferred to the atmosphere during transpiration or evaporation processes from soil surfaces. Usually latent heat is transferred into atmosphere due to convection and composes about 16 % of terrestrial energy loss.

Sensible Heat Flux H (W/m^2) is heat energy that is transported by a body that has a temperature higher than its surroundings via conduction, convection, or both. A temperature gradient must exist between the surface and the air above. Because air is such a poor conductor of heat, it is convection that is the most efficient way of transferring sensible heat into the air. When the surface is warmer than the air above, heat will be transferred upwards into the air as a *positive sensible heat transfer*. The transfer of heat raises the air's temperature but cools the surface. If the air is warmer than the surface, heat is transferred from the air to the surface creating a *negative sensible heat transfer*. Usually sensible heat flux composes about 5 % of terrestrial energy loss.

Energy balance of terrestrial surface depends on the daytime and night-time. By day, principal energy gain is related to net radiation and energy losses are due to latent heat flux (evaporation into air) and sensible heat flux (convection). By night, heat losses are caused by net radiation, while latent heat flux (condensation processes) and sensible heat flux (reverse convection) provide the energy gain.

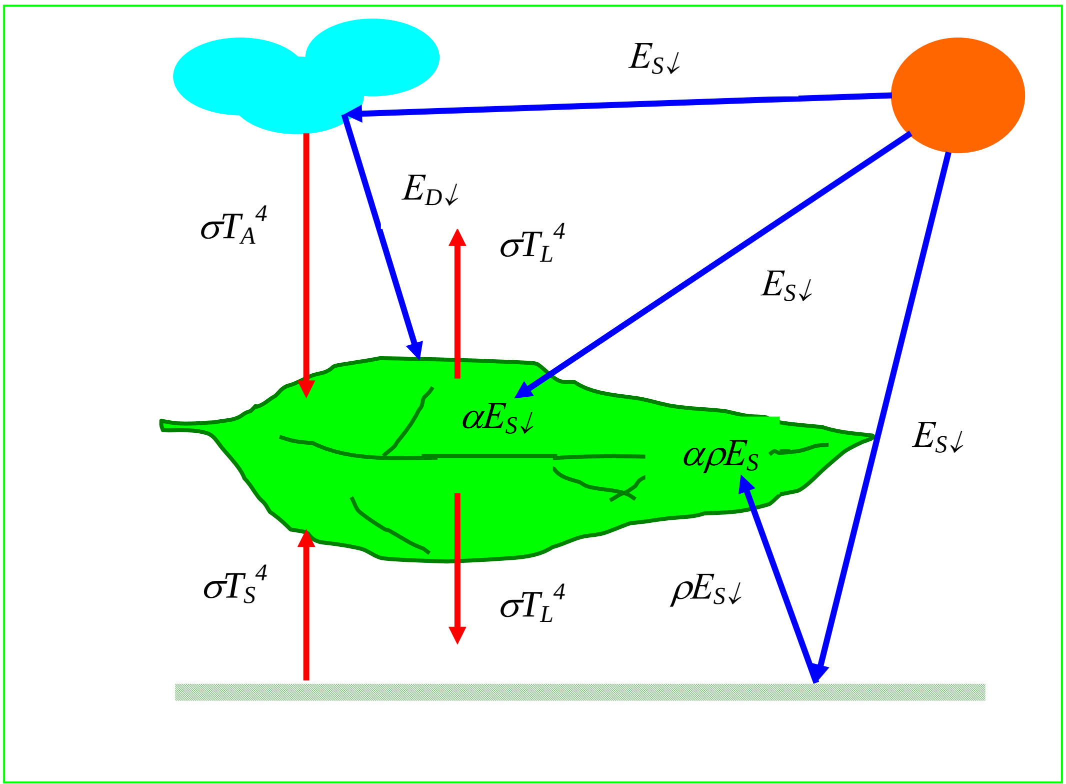
Energy Budget of a Single Leaf

Let's consider a single horizontal leaf, placed above a bare of soil. Its radiation balance is the algebraic sum of radiation exchanges of long and short wavelengths.

The net shortwave radiation is:

$$E_{netS} = E_{S\downarrow} + E_{D\downarrow} + \rho E_{S\downarrow}. \tag{15.12}$$

where ρ is the reflectivity of the Earth's surface.



The net longwave radiation is:

$$E_{netL} = \sigma T_A^4 + \sigma T_S^4 - 2\sigma T_L^4. \qquad (15.13)$$

Net radiation is the sum of all the gains and losses of radiant power by the leaf:

$$\alpha_l(E_S\downarrow + \rho E_S\downarrow) + E_D\downarrow = \sigma T_A^4 + \sigma T_S^4 - 2\sigma T_L^4, \qquad (15.16)$$

where α_l is absorption coefficient of the leaf.

Net radiation balance can be expressed as

$$R_{net} = \alpha\,(1 + \rho)\,E_S\downarrow + \sigma T_A^4 + \sigma T_S^4 - 2\sigma T_L^4. \qquad (15.17)$$

Balance Equation of a Single Leaf

A simple heat balance equation shows how the energy of equation (15.17) is used:

$$R_{net} = \varepsilon\sigma T_S^4 + H + \lambda E, \qquad (15.18)$$

where $\varepsilon\sigma T_L^4$ is the emitted radiation; H is the sensible heat loss; λE is the latent heat loss.

Here the sensible heat flux is determined as

$$H = J_C = h_c(T_L - T_A) = k_1 \upsilon^{0.5} D^{-0.5}(T_L - T_A), \qquad (15.19)$$

where k_1 = 9.14 $Jm^{-2}s^{-1/2}$; D is a characteristic dimension of the object; υ is the wind speed; T_a is the air temperature; and T_l is the leaf temperature.

Latent heat flux is the energy transferred to the atmosphere during transpiration processes from leaf surface which depends on two major factors: the *difference in water vapour concentration* between the leaf air spaces and the external air and, the *diffusional resisitance (r)* of this pathway. This concept of transpiration is analogous to the flow of electrons in an electric circuit. In this analog, resistances are associated with each part of the pathway; the major ones are the resistance at the stomatal pore (r_s) and the resistance due to the layer of unstirred air at the surface of the leaf (r_b) (the so-called *boundary layer*). Transpiration rate (E, in mol m^{-2} s^{-1}) may be related to diffusional resistances (r, in s m^{-1}) by the following equation:

$$E = \frac{e_{s,leaf} - he_{s,air}}{r_{leaf} + r_{air}}, \qquad (15.20)$$

where $e_{s,leaf}$ and $e_{s,air}$ – saturation vapour pressure in the leaf and the surrounding air correspondingly (kPa); $e_{sleaf} - e_{sair}$ is the vapour pressure gradient; h – relative humidity.

It is necessary to assume, that the stomatal air space of a leaf is normally saturated, and the atmosphere which surrounds the leaf is usually unsaturated. That's why the difference in water pressure between the internal air spaces of the leaf and the surrounding air is the *driving force* for transpiration.

The resistance of a leaf can be calculated as:

$$r_{leaf} = \frac{(r_i + r_s)r_c}{r_i + r_s + r_c}, \qquad (15.21)$$

where r_i is intracellular air-space resistance; r_s is stomatal resistance, and r_c is cuticular resistance.

Total resistance of a leaf and the boundary layer is:

$$r = r_{leaf} + r_{air}. \qquad (15.22)$$

Usually r_{air} depends upon leaf size (D in the direction of flow and W at right angles to D) and wind speed υ

$$r_{air} = k_2 \frac{W^{0.2} D^{0.3}}{\upsilon^{0.5}}, \qquad (15.23)$$

where $k_2 = 200\ s^{1/2}m^{-1}$.

The energy-budget relationships for a plant leaf can be written in such a form:

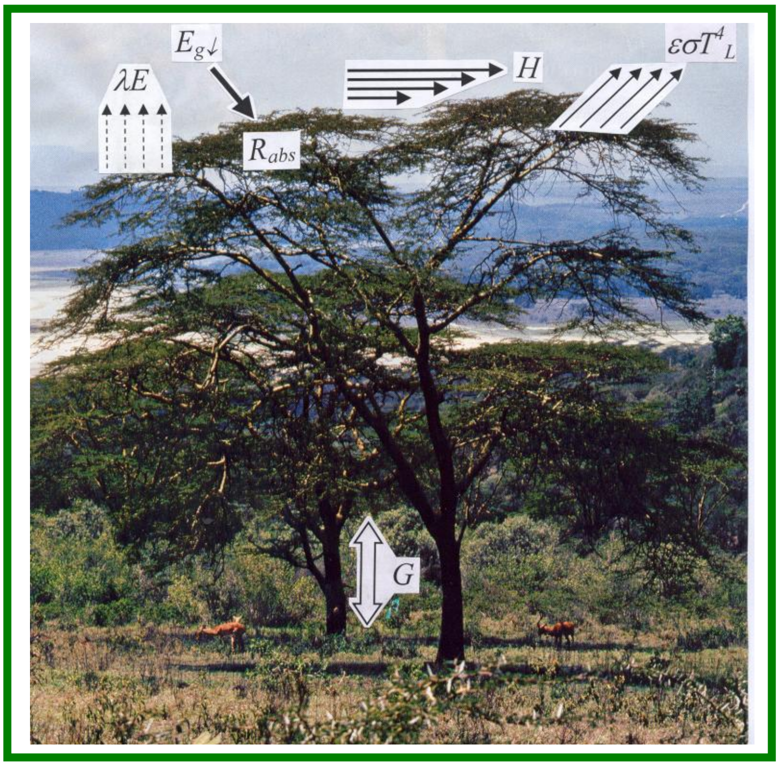
$$R_{net} = \varepsilon\sigma T_L^4 + k_1 \upsilon^{0.5} D^{-0.5} (T_L - T_A) + \lambda \frac{e_{s,leaf} - he_{s,air}}{r_{leaf} + r_{air}}. \qquad (15.24)$$

Energy Budget of the Plant

As the whole, energy balance of the whole plant is

$$R_{net} = G + H + \lambda E, \qquad (15.25)$$

where G is the rate of heat storage in the soil (W/m^2).

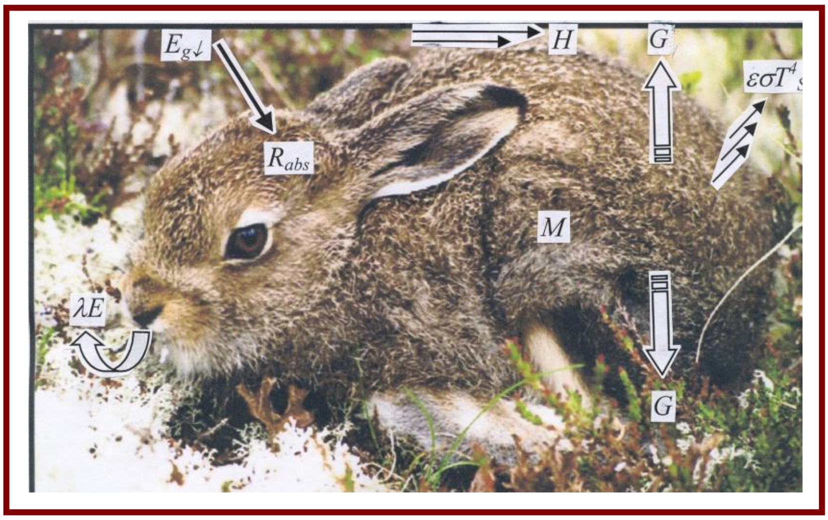


Energy Budget of Animal

The general energy budget of animal presents the sum of all the gains and losses of radiant energy at the animal's surface. It is described by the following equation:

$$R_{abs} + M = \varepsilon\sigma T_S^4 - H - G - \lambda E, \qquad (15.26)$$

where R_{abs} is the amount of radiation absorbed by the surface of the animal; M – the rate of metabolic heat production per unit surface area; $\varepsilon\sigma T_S^4$ – energy lost by radiation at the animal's surface; H – the rate of sensible heat loss; G – the rate of heat loss to the substrate by conduction; λE – the latent heat loss from evaporation of water from the animal surface.



Metabolism

The principal difference of animal's energy exchange is *metabolism* – the set of the chemical processes occurring within a living organism that are the basis of life, as they necessary for the maintenance the structure of living organism, response to their environments, growth and reproduction.

The rate M of metabolic heat production can be estimated either per unit surface area, or per unit body mass, as soon as surface area S and body mass m are related by the following expression:

$$S = 0.1m^{2/3}. \qquad (15.27)$$

The rate M_b of metabolic heat production per unit body mass is given by:

$$M_b = Cm^{3/4}, \qquad (15.28)$$

where C is a constant (C = 3–5% for endotherms and around 5% for poikilotherms at 20 ^{0}C). Here M_b is measured in W; m – in kg.

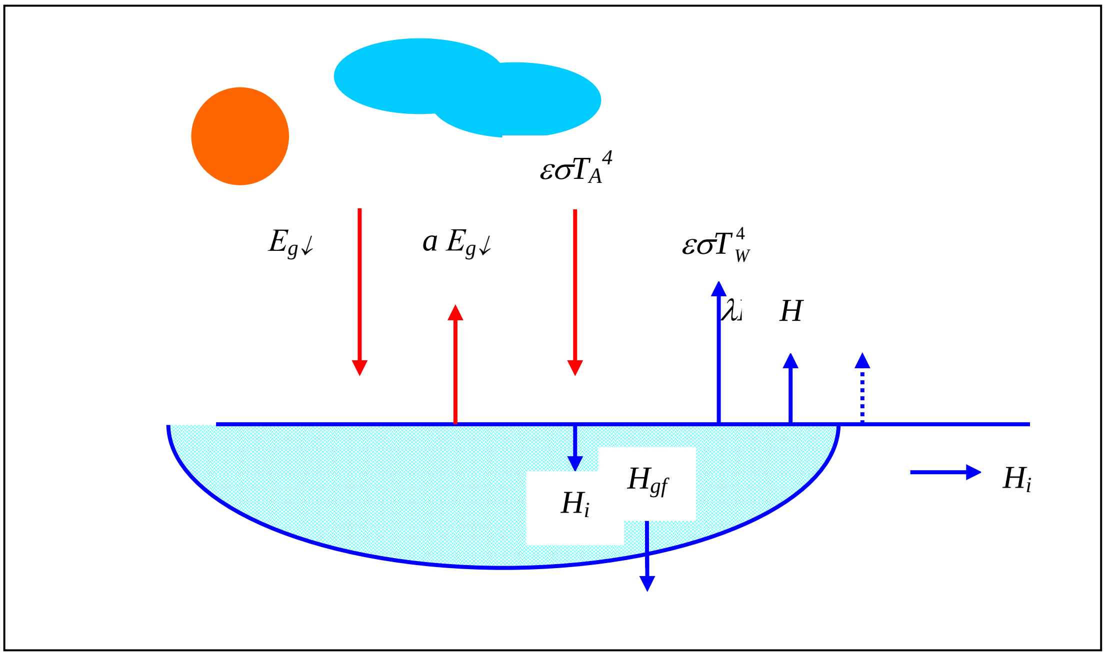
Typical values for M_b in endotherms range from 30 to 50 W/m^2 .

The Energy Budget of Watershed

Energy balance for water reservoirs can be presented in the following form

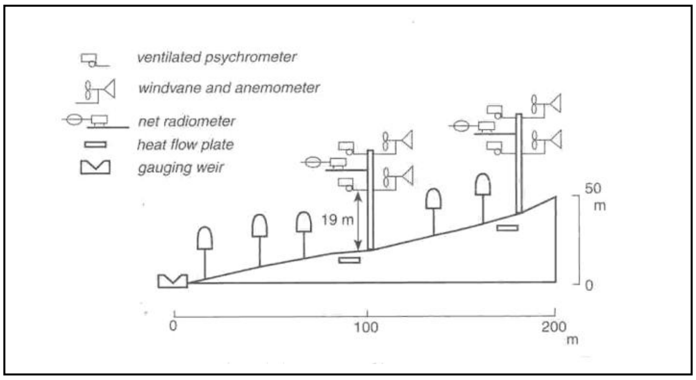
$$E_{net} + \varepsilon\sigma T_W^4 = H_i + H_{if} + H + \lambda E + H_{gf}, \qquad (15.29)$$

where $E_{net} = (1 - a)\, E_g\downarrow + \varepsilon\sigma T_A^4$ is net radiation of the sun; $(1 - a)\, E_g\downarrow$ – incoming short-wave solar radiation; $\varepsilon\sigma T_A^4$ – downward long-wave atmospheric radiation; $\varepsilon\sigma T_W^4$ – upward long-wave water radiation; H_i – increase in stored heat energy of water; H_{if} – net energy convected or conducted out of system by flow of water; H – the rate of sensible heat loss; H_e – energy used for evaporation; H_{gf} – heat flux into ground water.



Practical Applications

Evapotranspiration research in forest includes investigation of heat budget and canopy interception. Let's consider the methodology and results of observation of meteorological elements using heat balance method [Shimizu et al., 2003]. For this ionvestigation, two sets of meteorological observation towers were installed along the predominant wind direction in evergreen plantation watershed.



Two sets of meteorological observation towers.
After Shimizu et al., 2003.

In addition to towers, seven shallow wells and a gauging weir to measure total stream flow at the outlet of the watershed were installed. The stream flow from the entire watershed was measured automatically using a water gauge with a high-precision type of float. Measurements of zero-order basin runoff were recorded automatically using a pressure transducer. Precipitation was measured at an open site near the outlet of the watershed with a 0.5 mm tipping bucket rain gauge.

Psychrometers were used in these experiment^ the lower ventilated psychrometer (19 m) was located just above the tree crowns; the higher psychrometer was 3 m above the lower one. Therefore, the differences in dry and wet bulb tempratures reflected the gradient between 19 and 22 m. The ventilated Assmann psychrometers used an AC power supply; the standard reservoir was replaced by a larger one for approximately 2 weeks in the summer. This reservoir was refilled every week.

The net radiometer was located between the two psychrometers. A heat flow plate was buried at a depth of 0.05 m.

The heat balance method (using the Bowen ratio) was used to estimate evapotranspiration

$$R_{net} = G + \lambda E + H. \qquad (15.30)$$

As the diffusion coefficients of the latent and sensible heat fluxes can be considered equal in the boundary layer, the Bowen ratio is introduced and the latent heat flux is estimated as follows

$$\lambda E = \frac{R_{net} - G}{1 + \beta}, \qquad (15.31)$$

where

$$\beta = H / \lambda E. \qquad (15.32)$$

The Bowen ration is calculated by measuring the wet and dry bulb temperatures at the two levels, and using the psychrometric constant and the gradient of the saturated vapour pressure curve as follows

$$\beta = \frac{\gamma(TD_1 - TD_2)}{(\delta + \gamma)(TW_1 - TW_2) - \gamma(TD_1 - TD_2)}, \qquad (15.33)$$

where γ is a psychrometric constant; $TD_1 - TD_2$ is the difference in the dry bulb temperatures at the two heights; δ is the gradient of the saturated vapour pressure curve and $TW_1 - TW_2$ is the difference in the wet bulb temperatures at the two heights.

Such a method made it possible to measure the annual average precipitation, amount of runoff and losses as 2166, 1243, and 923 mm, respectively; average annual evapotranspiration at the tower built in the centre of the watershed as 902 mm and at the other tower, further upslope, as 875 mm. The mean net radiation was about 2.6 GJ/$m^2 \cdot$year.

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