# PART I

# CLIMATIC FACTORS

# 1

# PRESSURE

## 1.1 DEFINITION OF PRESSURE

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

$$p = \frac{F}{S}, \tag{1.1}$$

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:

$$p = \sum_{\Delta S \to 0} \frac{\Delta F}{\Delta S} = \frac{dF}{dS}. \tag{1.2}$$

The SI unit for pressure is *pascal* (1 Pa = 1 N/m$^2$ = 1 kg/m·s$^2$). The following pressure units are also used:

1 Pa = $9.87 \times 10^{-6}$ atm = $7.5 \times 10^{-3}$ mmHg = 0.000295 inHg = $7.5 \times 10^{-3}$ Torr = $10^{-5}$ bar = $1.45 \times 10^{-4}$ psi;

*Methods of Measuring Environmental Parameters*, First Edition. Yuriy Posudin.

1 bar = $10^5$ Pa = 0.987 atm = 750.06 mmHg = 29.53 inHg = 750.06 Torr = 14.504 psi;

1 atm = $1.01325 \times 10^5$ Pa = 1.01325 bar = 760 mmHg = 29.92 inHg = 760 Torr = 14.696 psi;

1 mmHg = 0.03937 inHg = 1 Torr = $1.3332 \times 10^{-3}$ bar = 133.32 Pa = $1.315 \times 10^{-3}$ atm = $19.337 \times 10^{-3}$ psi;

1 psi = 6894.76 Pa = $68.948 \times 10^{-3}$ bar = $68.046 \times 10^{-3}$ atm = 51.715 mmHg = 2.04 inHg = 51.715 Torr;

1 inHg = 25.4 mmHg = 3386.38816 Pa = 0.03342 atm = 25.4 Torr = 0.03386 bar = 0.49 psi.

A pressure of 1 Pa is small; the following non-SI metric units of pressure such as hectopascal (1 hPa = 100 Pa) or millibar (1 mbar = $10^{-3}$ bar) are used in meteorology and weather reports. The National Weather Service of the United States uses both inches of mercury (inHg) and hectopascals (hPa) or millibars (mbar). The pound per square inch (psi) is still popular in the United States and Canada.

## 1.2 ATMOSPHERIC PRESSURE

*Atmospheric pressure* is defined as the weight of a column of atmospheric air that acts on a given unit of surface area. Air is a mixture of gases, solids, and liquid particles. As a whole, atmospheric pressure depends on height; also it is characterized with horizontal distribution. The density and temperature of atmospheric air also depends on height.

The idea of a uniform distribution of atmospheric molecules within a volume of air is erroneous. Molecules are subject to the Earth's gravitational field; in addition, there is the effect of their thermal motion on the spatial distribution of the molecules. The combined action of the gravitational field and thermal motion leads to the state that is characterized by a decreasing gas concentration and pressure with increasing height.

Atmospheric air can be considered as an ideal gas, which can be described as follows:

$$p_A V_A = \frac{m_A}{M_A} R T_A, \tag{1.3}$$

where $p_A$ is the pressure of the air; $V_A$ is the volume of the air; $m_A$ is the mass of the air; $M_A$ is the molar mass of atmospheric air ($M_A = 0.029$ kg/mol for dry air, $M_A = 0.018$ kg/mol for water vapor); $R = 8.314$ J/K·mol is the molar gas constant; $T_A$ is the absolute temperature of the air.

Let us derive an expression for the pressure of an air in a container whose elementary volume is assumed to be in the shape of a cube (White, 2008). There are three forces that act on this volume. The force due to the pressure of the air contained on this volume is:

$$F_{\downarrow} = p_{\downarrow} S, \tag{1.4}$$

where $S$ is the base area of the elementary volume.Simultaneously the force of the gas, which is located below, acts in the opposite direction:

$$F_{\uparrow} = -p_{\uparrow} S. \tag{1.5}$$

The third force that acts on the elementary volume is the weight of the air:

$$P = \rho g V = \rho g S h, \tag{1.6}$$

where $\rho$ is the air density; $g$ is the acceleration due to gravity; $V$ is the elementary volume; $h$ is the edge length of the cube.The balance of these forces can be written as

$$F_{\downarrow} + F_{\uparrow} + P = p_{\downarrow} S - p_{\uparrow} S + \rho g S h = 0, \tag{1.7}$$

or

$$p_{\downarrow} - p_{\uparrow} = -\rho g h. \tag{1.8}$$

This equation can be written for infinitesimal changes of pressure in the differential form

$$dp = -\rho g dh. \tag{1.9}$$

The density $\rho_A$ of the atmospheric air can be expressed as

$$\rho_A = \frac{m_A}{V_A} = \frac{M_A p_A}{R T_A}. \tag{1.10}$$

The atmospheric pressure decreases with the change in altitude from $h$ to $h + dh$, according to Equation 1.9

$$\frac{dp_A}{dh} = -\rho_A g. \tag{1.11}$$

Combining (1.10) and (1.12), we can obtain the expression

$$\frac{dp_A}{p_A} = -\frac{M_A g}{R T_A} dh, \tag{1.12}$$

which by integrating this expression from the surface to the altitude $z$ leads to the *barometric formula*

$$p_A(z) = p_A(0)\exp[-(gM_A/RT_A)]z, \tag{1.13}$$

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 (9.8 m/s$^2$); $M_A$ is the molar mass of the gas ($M_A = 0.029$ kg/mol for air); $R$ is the universal gas constant (8.314 J/K·mol); $T_A$ is the absolute temperature.

This equation indicates an exponential decrease in pressure with increasing elevation.

The meteorologists use the term "isobar"—a line connecting points of equal atmospheric pressure, which are depicted on weather maps. The rules for drawing isobars are

- Isobar lines may never cross or touch.
- Isobar lines may only pass through pressures of 1000 mbar ± 4 mbar.

In other words, allowable lines are 992, 996, 1000, 1004, 1008, and so on.

**Example** Find the atmospheric pressure at 10,000 m.

***Solution*** The atmospheric pressure can be found as

$$\begin{aligned}
p_A(z) &= p_A(0)\cdot \mathrm{e}^{[-(gM_A/RT_A)]z} \\
&= 1.01325\times 10^5\,\mathrm{Pa}\cdot \mathrm{e}^{\left[-\frac{(0.029\,\mathrm{kg/mol})\,(9.8\,\mathrm{m/s^2})\,(10^4\,\mathrm{m})}{(8.314\,\mathrm{m^2\cdot kg/s^2\cdot K\cdot mol})\,(223.25\,\mathrm{K})}\right]} \\
&= 1.01325\times 10^5\,\mathrm{Pa}\cdot \mathrm{e}^{-1.531} = 1.01325\times 10^5\ \mathrm{Pa}\cdot 0.2163 = 0.219\times 10^5\ \mathrm{Pa}.
\end{aligned}$$

**Exercises**

1. Determine the atmospheric pressure at the altitude of the peak of Mount Everest (8848.82 m).
2. At what altitude is the atmospheric pressure reduced to 0.5 atm? The temperature is 260 K.
3. What is the temperature in Lhasa, Tibet (3650 m), if the atmospheric pressure is 652 mbar?

**Constructive Tests**

1. To what altitude is the barometric formula valid?
2. What is the explanation for the exponential distribution of atmospheric pressure? Why are atmospheric molecules and particles not deposited on the Earth's surface due to the influence of gravity?

***Extreme Situations***

The highest barometric pressure ever recorded on Earth was 32.31 inHg (1094 hPa), measured in USSR, on December 31, 1968, in northern Siberia. The weather was clear and very cold at the time, with temperatures between 233.15 and 215.15 K.

The lowest pressure ever measured was 25.69 inHg (870 hPa), set on October 12, 1979, during Typhoon Tip in the western Pacific Ocean. The measurement was based on an instrumental observation made from a reconnaissance aircraft.

## 1.3 PHYSIOLOGICAL EFFECTS OF DECREASED AIR PRESSURE ON HUMAN ORGANISM

People who reach high altitudes suffer from *mountain sickness* (Folk, 1998): They feel changes in pulse and breathing rate, anorexia (an eating disorder due to loss of appetite), and a loss of body weight with increasing height. The principal symptoms of mountain sickness are dyspnea (difficult breathing), tachycardia (heart rate in excess of 100 beats per minute), malaise (vague body discomfort), nausea and vomiting, insomnia, and lassitude (a state or feeling of weariness, diminished energy, or listlessness). The prevalence of *mountain sickness* can be explained by the effect of altitude on the partial pressure of oxygen in the lung alveoli.

## 1.4 PHYSIOLOGICAL EFFECTS OF ALTITUDE ON ANIMALS

There are a number of animals that have adapted for living at high altitudes. The Lake Titicaca frog, likewise, lives at an altitude of 3812 m. The frog exhibits increased gas exchange due to extensive skin folds, and high hematocrit and erythrocyte concentrations. Thus, the capacity of the frog for transporting oxygen is substantially increased.

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. They demonstrate the ability to accurately assess their capacity for work and refuse to be pushed beyond a safe limit. Such animals may be mentioned as the vicuna (5000–6000 m), domestic sheep (up to 5250 m), and horses (up to 4600 m). Birds, however, hold the high altitude records: condors (7600 m), geese (8534 m), chough (9000 m), and griffon vulture (11,278 m).

## 1.5 EFFECTS OF ALTITUDE ON 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 the 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 (Posudin, 2004).

## 1.6 VARIATION OF PRESSURE WITH DEPTH

Let us consider some liquid in a vessel. All points at the same depth feel the same pressure. Consider a cylinder of cross-sectional area $A$ and height $dy$ (Serway, 1990). The upward force that acts on the bottom of cylinder is $F_1 = pA$, and the downward force that acts on the top is $-F_2 = (p + dp)A$.

The weight of the cylinder is

$$dP = \rho g dV = \rho g A dy, \tag{1.14}$$

where $\rho$ is the density of the liquid.

In equilibrium, the resultant force is zero:

$$\sum F_y = pA - (p + dp)A - \rho g A dy, \tag{1.15}$$

Hence,

$$-dpS - \rho g S dy = 0, \tag{1.16}$$

or

$$\frac{dp}{dy} = -\rho g, \tag{1.17}$$

where the sign "minus" indicates that the increase of elevation corresponds to a decrease of pressure.

If $p_1$ and $p_2$ are the pressures at the levels $y_1$ and $y_2$ correspondingly, the following expression can be written as

$$p_2 - p_1 = -\rho g(y_2 - y_1). \tag{1.18}$$

If the vessel is open from the top, the pressure at the depth $d$ can be determined as

$$p = p_{\mathrm{A}} + \rho g d, \tag{1.19}$$

where $p_{\mathrm{A}}$ is atmospheric pressure; $\rho$ is the density of the liquid; $d$ is the depth; $g$ is the acceleration due to gravity.

This expression can be rewritten as

$$p = p_A + \frac{\rho g d A}{A} p_A + \frac{mg}{A} = p_A + \frac{P}{A}. \tag{1.20}$$

Thus, the absolute pressure $p$ at a depth $d$ below the surface of a liquid exceeds the atmospheric pressure by the value $\rho g d$, which corresponds to the pressure that is created by the weight of the liquid column of cross-sectional area $A$ and height $h$.

Thus, the pressure at the depth $d$ is determined for the opened vessel by Equation 1.19

$$p = p_A + \rho g d, \tag{1.21}$$

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

In such a way, the absolute pressure $p$ at a depth $d$ below the surface of a liquid open to the atmosphere is greater than atmospheric pressure by an amount $\rho g d$.

**Example** Calculate the pressure at the bottom of the Marianas Trench (depth 11,043 m). Assume the density of water is $1 \times 10^3$ kg/m$^3$ and take $p_A = 1.01 \times 10^5$ Pa.

***Solution*** Using formula (1.21), we can find the pressure:

$$p = p_A + \rho g d = 1.01 \times 10^5 \text{ Pa} + (1 \times 10^3 \text{ kg/m}^3)(9.8 \text{ m/s}^2)(11{,}043 \text{ m}) = 109 \text{ MPa}.$$

## 1.7 PHYSIOLOGICAL EFFECTS OF INCREASED PRESSURE ON HUMAN ORGANISM

***Pressure Problems.*** The representative of some professions (Arabian sponge divers, Australian pearl divers, Japanese and Korean Ama) support their living by diving into the sea without any special equipment. When a diver descends, he is sensitive to the surrounding water pressure which increases at a rate of one atmosphere for each 10 m of descent (i.e., $\Delta p = 1$ atm for $\Delta d = 10$ m). The pressure of the surrounding water is transmitted to all internal parts of the body and the state of pressure equilibrium is established—the internal pressure of the body is equal to the surrounding pressure. During ascent and descent, the diver must support the same pressure of air in his lungs 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 in his lungs according to Equation 1.21. When he is ascending, the pressure at the water surface will be 1 atm, while the pressure in his lungs is 3 atm. This pressure difference can lead to the rupture of his lungs. Such a situation is called *pneumothorax.*

***Influence of Nitrogen.*** The air we breathe consists of 79% of nitrogen and our blood is full of dissolved nitrogen. According to pneumothorax, 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. The great pressure of air in the lungs provokes the formation of the bubbles into the blood vessels.

If bubbles are formed due to rapid decompression, the diver will suffer the effects of a painful disease called the *caisson disease* (from French *Caisse,* a chest) or the *bends*, which lead to neuralgic pains, paralysis, distress in breathing, and often collapse.

***Oxygen Poisoning.*** When a diver is under water, 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 is increased, this oxygen support by hemoglobin is stopped, the tissues remain saturated, and the convulsions induced by high-pressure oxygen can take place.

***Carbon Dioxide Influence.*** A great amount of carbon dioxide (more than 10%) at the depth can depress the cellular metabolism of the respiratory center; the diver develops lethargy and narcosis, and finally becomes unconscious.

## 1.8 PHYSIOLOGICAL EFFECTS OF PRESSURE ON DIVING ANIMALS

The deep-sea environment is characterized by a considerable high hydrostatic pressure which increases by approximately 1 MPa ($10^6$ Pa) for every 100 m of depth. The marine depths investigator Jacques Piccard observed through the illuminator of his bathyscaphe shrimp and fish at the depth about 10,912 m. Some invertebrates and bacteria have been found near the bottom of the Marianas Trench (depth 11,043 m, pressure about 110 MPa). 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 m—northern elephant seal, *Mirounga angustirostris*; 2000–3000 m—sperm whale, *Physeter catodon*; 7250 m—sea urchin, *Echinoidea*; 7360 m—sea star, *Asteroidea*; 8370 m—cuskeel fish, *Ophidiidae*; 10,190 m—sea cucumber, *Holothurioidea* (Folk, 1998).

What are the principal mechanisms of such depth adaptation of marine animals? The first peculiarity is related to the ability of these animals to exhale before diving: for example, cetaceans can exhale about 88% of its lung air with a single breathe while humans approximately 12%. Their lungs are collapsed quickly preventing atmospheric gases (nitrogen, oxygen) from entering the bloodstream. Another feature is the ability of diving animals to use oxygen from the blood which is characterized with high blood volume and high hematocrit (a number of blood cells). In such a way, the skeletal muscle tissue of these animals contains about 47% of overall body oxygen. The large amount of hemoglobin in the muscles is responsible for their deep red color. The diving animals have about 10 times more of myoglobin in the muscles than terrestrial animals. It is necessary to mention the sufficient ability of diving animals to decrease the heart rate during the diving in comparison to the sea surface situation: for instance, a muskrat has 320 beats per minute before dive and 34 beats per minute only at the depth; on land, seal has a heartbeat of 107 beats per minute, but at the depth its pulse decreases to a mean of 68 beats per minute. Such abilities of diving animals to collapse the lungs, to store myoglobin in their muscles, and to use oxygen located within the muscle cells and the blood can make it possible to escape the bends (Posudin, 2004).

## REFERENCES

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