

## ***Introduction to environmental physics***

Environmental physics can be defined as the response of living organisms to their environment within the framework of the physics of environmental processes and issues. It is structures within the relationship between the atmosphere, the oceans, land, soils and vegetation.

Environmental physics embraces the following themes:

- Human environment and survival physics.
- Built environment.
- Urban environment.
- Renewable energy.
- Remote sensing.
- Weather.
- Climate and climate change.
- Environmental health.

### **The human environment:**

Living organisms have to adapt and survive in a variety of environmental conditions, including hot and cold climates. They are thermodynamic entities characterized by energy flows both within the body, and between the body and its environment. For people to survive, the core body temperature has to be maintained within a narrow temperature range of 35-40 °C. The rate of these energy transfers and the mechanism of thermoregulation are governed by the following laws and concepts of physics:

- Laws of thermodynamics,
- Principles of entropy, enthalpy, and the Gibbs free energy,
- Principles of conduction, convection, radiation and evaporation,
- Newton's law of cooling, and
- Wien's and Stefan-Boltzmann radiation laws.

Human beings have managed to live in all the different environments present throughout the Earth. Mammals, including humans, have the remarkable ability to maintain a constant body temperature, in spite of dramatic changes in environmental conditions. They are called *homeotherms*. They sustain their body temperatures by adjusting the rate of energy transfer and energy production (transformation).

### **Energy transfers:**

Energy can be transferred from one point to another by the following mechanisms:

- 1- Conduction.
- 2- Convection.
- 3- Radiation.
- 4- Evaporation.

The physics of each of those mechanisms will be discussed in turn.

#### **1) Conduction:**

Thermal conduction is the process by which energy can be transferred between two points in a material at different temperatures. In solids this is achieved in two ways:

- 1- Through molecular vibrations transferring energy through the crystal lattice.
- 2- Through the mobility of free conduction electrons throughout lattice.

J. Fourier had discovered that the *rate of flow of thermal energy* ( $dQ/dt$ ) through a material depends on the cross-sectional area,  $A$ , the length or thickness of the material ( $L$ ), and the difference in temperature between the two sides ( $\Delta T$ ).

$$\Delta T = T_1 - T_2$$

This can be expressed as

$$dQ/dt = -kA \cdot \Delta T/L$$

where  $k$  is the thermal conductivity of a material. The effectiveness of a material as an insulator can be determined by measuring its thermal conductivity. Good thermal conductors like copper have a high thermal conductivity, e.g.  $380 \text{ Wm}^{-1}\text{K}^{-1}$ , while poor conductors like water have a low thermal conductivity, i.e.  $0.59 \text{ Wm}^{-1}\text{K}^{-1}$ . The ratio of the temperature difference divided by the length is called the *temperature gradient*.

The minus sign in the above equation is significant. It shows that the flow of energy is from the region at the higher temperature to that at the lower temperature, i.e. it flows along the temperature gradient. It implies that energy flow is unidirectional.

*Example:*

A rambler is walking up a steep hillside in January. He is wearing clothing 1 cm thick, his skin temperature is  $34 \text{ }^\circ\text{C}$  and the exterior surface is close to freezing at  $0 \text{ }^\circ\text{C}$ . Determine the rate of flow of energy outwards from his body, through thermal conduction, when:

- It is fine dry. Assume that the thermal conductivity for clothing, under dry conditions, is  $0.042 \text{ Wm}^{-1}\text{K}^{-1}$ .
- It has been raining heavily and the rambler is soaked. The thermal conductivity is now  $0.64 \text{ Wm}^{-1}\text{K}^{-1}$ . Assume that the walker has surface area of  $1.84 \text{ m}^2$ .

*Solution:*

- Apply the Fourier's law of thermal conduction.

$$dQ/dt = -kA \cdot dT/L$$

$$= -0.042 \cdot 1.84 \cdot (34-0) / 0.01$$

$$= -263 \text{ W.}$$

- Applying the Fourier's law again,

$$dQ/dt = -0.64 \cdot 1.84 \cdot (34-0) / 0.01$$

$$= - 4004 \text{ W.}$$

When clothing becomes wet, it becomes a better conductor for the outward dissipation of energy because water has a higher thermal conductivity than dry clothing. This is why jeans are inappropriate trouser-ware for strenuous outdoor pursuits in wet weather.

## **2) Convection**

Convection occurs when thermal energy is transferred by the motion of a fluid. The fluid can be either a liquid or a gas. The air in close proximity to any living body will warm up due to heat radiating from the body and expand, so becoming less dense and rise. Colder and denser air will take its place down and convection current will be set up. A similar process occurs but on much larger scale in the Earth's atmosphere.

There are two types of convection:

- (i) Natural (when fluids move without forcing).
- (ii) Forced (when the fluid is forced, such as blowing over a hot cup of tea).

Of particular importance for the human environment is forced convection and the Newton's law of cooling provides a physical model of it.

### ***Newton's law of cooling:***

A number of factors will influence the rate of convection from an object in a fluid, including the temperature of the object, the shape, the size, the temperature of the fluid and the type of flow relative to the object. Newton determined that the rate at which energy is lost from a body  $dQ/dt$  is directly proportional to the difference between the body's temperature ( $T$ ), and environmental temperature ( $T_0$ ):

$$dQ/dt = - kA \cdot \Delta T.$$

This equation represents Newton's law of cooling, where  $k$  is proportionality

constant whose magnitude depends upon the nature and surface area of the body, and is called *convective energy transfer coefficient*. For a plate in still air  $k$  is  $4.5 \text{ Wm}^{-2}\text{K}^{-1}$  and is about  $12 \text{ Wm}^{-2}\text{K}^{-1}$  when air flows over it at  $2 \text{ m/s}$ . Strictly, this law applies to objects cooling in a draught, such as blowing over a cup of tea. It does not apply to humans as the process of metabolism attempts to maintain the body temperature at a constant value. However, walking against a strong wind or in a wind tunnel is a reasonably good approximation of this law.

*Example:*

A student volunteers to take part in the following simulations of convective energy loss:

- He is placed in a wind tunnel in which air, at  $-2 \text{ }^\circ\text{C}$ , blows through at  $40 \text{ km/h}$ .
- He is placed in a flow of water, which is at  $12 \text{ }^\circ\text{C}$ . The velocity of flow is  $0.5 \text{ m/s}$ . In each case calculate:

(i) The convective energy transfer coefficient.

(ii) The convective energy transfer flux,  $dQ/dt$ .

Assume  $A = 1.8 \text{ m}^2$  and the skin temperature is  $31^\circ\text{C}$ . Assume convective energy transfer coefficient  $k = 44.8 \text{ Wm}^{-2}\text{K}^{-1}$  for  $40 \text{ km/h}$  speed of flow, and  $k = 34.4 \text{ Wm}^{-2}\text{K}^{-1}$  for  $0.5 \text{ m/s}$ .

*Solution:*

Applying Newton's law for cooling, we have:

- $dQ/dt = 2661 \text{ W}$ .
- $dQ/dt = 1176 \text{ W}$ .

### **3) Radiation:**

Radiation plays an important role in the energy balance of human beings. It is the process in which energy can be transferred in the form of electromagnetic waves from one point to another through a vacuum. All objects release energy in the form of electromagnetic waves. The best absorbers usually make the best emitters of radiation and these are called *black-body*. Human beings emit radiation in the infrared band.

There are two experimental laws that usually we use to explain radiation:

#### 1) *Wien's law.*

Wien's law tells us about the wavelength,  $\lambda_m$ , that the body at the temperature,  $T$ , radiates with the maximum intensity.

$$\lambda_{\max} \cdot T = b$$

where  $b$  is a constant, and for the black-body is  $b = 3 \cdot 10^{-3} \text{ m} \cdot \text{K}$ .

#### 2) *Stefan-Boltzmann law.*

Stefan-Boltzmann law explains the total amount of radiation energy per second (or as power) from a black-body, and was discovered to be proportional to the fourth power of the temperature,  $T$ , and the area,  $A$ , of the surface emitting the radiation

$$P = \sigma AT^4$$

where  $\sigma$  is Stefan's constant, and for the black-body is  $\sigma = 5.7 \cdot 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$ .

No real body is a perfect black-body radiator, and to distinguish between a perfect black-body and real bodies the idea of *emissivity*,  $\varepsilon$ , has been introduced.

Thus, for the radiation power we have:

$$P = \varepsilon \sigma AT^4$$

An object release energy in an environment which itself is radiating energy. Then the object will absorb energy. This means that the net rate of

radiation emitted is the difference between the energy emitted by the object and the energy absorbs from its surroundings.

*Example:*

A person sitting reading a book releases radiant energy of between 70 and 100 W. Calculate how much energy the person is radiating. Assuming that the emissivity for the human body is 0.5, with an average surface temperature of 35 °C, that room temperature is 20 °C, and the body surface area is 1.8 m<sup>2</sup>.

*Solution:*

Applying the Stefan-Boltzmann law,

$$P = 83.6 \text{ W.}$$

#### **4) Evaporation:**

Evaporation constitutes a fourth method for obtaining an energy balance for energy transfer. Evaporation is important in understanding weather and climate generally, and clouds in particular.

*Evaporation is the process whereby a liquid can be transformed into a vapor.* This implies a phase change, or change of state, and it is an example of a latent heat change, in which the evaporative energy loss depends on the mass of the liquid and the energy required to vaporize the liquid

$$Q = mL,$$

where:

$Q$  : the energy extracted or supplied to bring about a phase change.

$m$  : the mass of liquid to be vaporized.

$L$  : the specific latent heat of vaporization. For pure water,  $L = 2.25 \cdot 10^6$  J/kg, but sweat, which is 99 % water with sodium chloride as solute, is an electrolyte with  $L = 2.43 \cdot 10^6$  J/kg. For humans and animals  $L$  depends on temperature.

As sweat vaporizes, the energy to achieve this has come from the hotter body. The net result is a cooling effect, and the surface temperature of the body decreases. The rate of evaporation depends on the surface area, the temperature difference, the humidity and (therefore, the difference in vapor pressure) the rate of sweating and the velocity of air flow.

The rate of evaporation from the body can be expressed as:

$$dQ/dt = hA(p_s - p_0),$$

where

$h$ : the evaporative energy transfer coefficient.

$A$  : the area of the skin's surface.

$p_s$  : the water vapor pressure adjacent to the skin.

$p_0$  : the water vapor pressure in the surroundings air. The vapor pressure at the skin's surface depends on the environmental humidity and the sweating rate.

**Question:**

During a warm day a walker loses 1.5 kg of perspiration by evaporation. Given that the latent heat of vaporization is 2.25 MJ/kg, calculate how much thermal energy is required to achieve this. (**Answer:**  $3.375 \times 10^6$  J)

$$dQ/dt = hA(p_s - p_0),$$

$$Q = mL,$$

## Structure and composition of the atmosphere

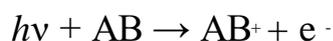
The Earth's atmosphere is a gaseous envelope, retained by gravity, surrounding the Earth. The density falls rapidly with height: 90 % of the mass of the atmosphere is contained within the first 20 km, 99.9 % within the first 50 km. The atmosphere becomes increasingly tenuous with increasing height until at about 1000 km.

- The temperature decreases with height at a rate of 6 °K/km (up to about 15 km), but the strongest horizontal temperature gradients (associated with warm or cold fronts) are about 0.05 °K/km.

The atmosphere is divided into regions characterized by their temperature. Each layer is called a *sphere* and the boundary between layers is called a *pause*

The boundary is named from the lower layer. The layers are:

- ❖ **Troposphere** (0-10 km). This is the lowest and contains 80 % of the mass. Almost all the weather is confined to the troposphere. In particular, it contains the clouds. The temperature falls linearly with height until at the top of the troposphere the temperature is approximately  $-50^{\circ}\text{C}$ .
- ❖ **Stratosphere** (10-50 km). Above the tropopause the temperature begins to rise again until at about 50 km the temperature is about  $+10^{\circ}\text{C}$ . The upper part of the stratosphere contains ozone – an essential molecule for life on Earth since it filters out (harmful) UV radiation.
- ❖ **Mesosphere** (50-85 km). Above the stratopause the temperature falls rapidly to about  $-80^{\circ}\text{C}$ . This is the coldest region of the atmosphere.
- ❖ **Ionosphere** (100-200 km). This is an intensely ionized region of the atmosphere and the temperature rises rapidly. Solar UV ionizes the molecules of the atmosphere



- ❖ **Thermosphere** (200-500 km). Temperature rises rapidly and varies strongly with the time of day, degree of solar activity and latitude. Variation between 400 °C and 2000 °C possible.
- ❖ **Exosphere** (500- about 1000 km). Atoms and molecules are sparse and can escape into space.
- ❖ **Magnetosphere** (above 1000 km). In this region the Earth's magnetic field interacts with the solar wind and traps charged particles (electrons and protons).

In the troposphere, stratosphere and mesosphere, mixing mechanisms ensure that there is essentially a constant chemical composition with an N<sub>2</sub>/O<sub>2</sub> ratio of about 4:1. This uniform composition gives these three regions the collective name of the **homosphere**

Above 100 km the ratio changes as a function of height. This (upper) region is called the **heterosphere**. The atmosphere contains a number of trace gases whose concentration does change with height. The most important gases are:

- Ozone – concentrated in the stratosphere (sometimes called the ozonosphere)
- Water – very variable concentration throughout the homosphere,
- Carbon dioxide – important greenhouse gas in the upper troposphere (0.03 % of the atmosphere).

### **Residence time:**

The *residence time* ( $\tau$ ): is the mean life time of a gas molecule in the atmosphere. This is as important as the concentration.

Indeed, when considering pollutants, it is the most important parameter. It is given by

$$\tau = \langle m \rangle / \langle F \rangle$$

where  $\langle m \rangle$  is the total average mass of the gas in the atmosphere

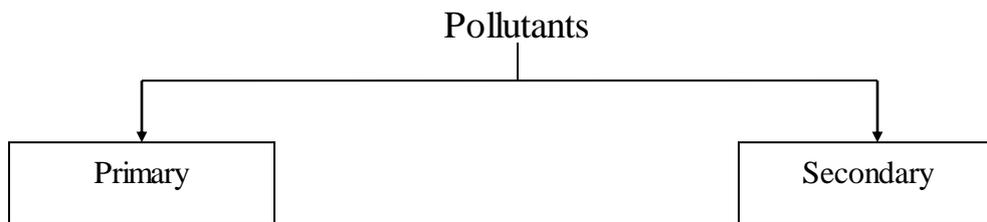
$\langle F \rangle$  is the total average influx (or out-flux).

$1/\tau$  is, therefore, the rate of turn over of the gas.

Using the residence time as a measure, we can divide the constituents of the atmosphere into three categories:

1. *Permanent*:  $\tau$  is very long (order of a few million years), e.g.  $N_2$ ,  $O_2$ , rare gases ( $CO_2$  but see also later).
2. *Semi-permanent*:  $\tau$  is of order months to years, e.g.  $CH_4$ ,  $N_2O$ ,  $CO$ ,  $CFC_s$ ,
3. *Variable*:  $\tau$  is of order days to weeks, e.g. ozone  $O_3$  (cycle in the stratosphere),  $H_2O$  (cycle in the troposphere),  $SO_2$  and  $H_2S$  (acid rain),  $NO_2$ ,  $NH_3$  (car exhausts) but also part of the nitrogen cycle.

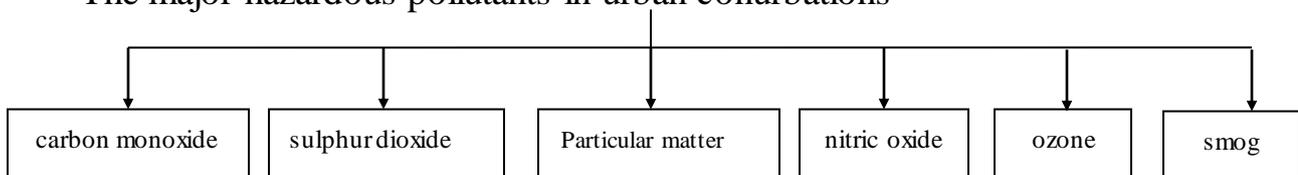
### Photochemical pollution



Primary pollutants are the chemical species emitted directly

- Are those formed from primary pollutants by local chemistry.
- The greatest damage often comes from the secondary pollutants rather than the primary. For example, while sulphur dioxide might be emitted from a power station its conversion into sulphuric acid is more damaging to the local environment.

### The major hazardous pollutants in urban conurbations



## Atmospheric aerosol

An aerosol contains solid or liquid particles in suspension (e.g. dust particles). In the atmospheric aerosol, particles arise from:

- Combustion – forest fires or industry (soot),
- Gas phase reactions (particles of sulphates or nitrates),
- Dispersion of solids (wind and water erosion of rocks),
- Dispersion of salts from the sea (sea-spray), and
- Volcanoes.

Typical concentrations are  $10^3$  particles  $\text{cm}^{-3}$  (over the ocean),  $10^4$  particles  $\text{cm}^{-3}$  (over the country),  $10^5$  particles  $\text{cm}^{-3}$  (over cities). The size ranges from aggregates of a few hundred molecules (diameter about 1 nm) to the largest particles (about 10  $\mu\text{m}$ ). The removal of the aerosol from the atmosphere depends on the size of the particles.

## Atmospheric pressure

We know that in climbing mountains both pressure and temperature decreased with increasing height. It can be shown that the pressure (in the troposphere) decreases by the following expression:

$$p = p_0 \cdot e^{-gh/RT}$$

where  $p_0$  is the atmospheric pressure at the surface ( $h = 0$  m), and  $p$  the pressure at a height  $h$ . Since the pressure falls exponentially with height, 90 % of the mass of the atmosphere is contained within the first 21 km, and 99.9 % in the first 50 km. The pressure therefore drops from 105 Pa at the Earth's surface to 104 Pa at 20 km, and to 102 at 50 km. The temperature also falls with altitude and it is called the *lapse rate* ( $dT/dz$ ).

## Ozone:

Ozone is only minor constituent of the Earth's atmosphere forming 0.2 % of the terrestrial atmosphere mass, the concentration of ozone is in the range 0.005-0.05 particles per million (ppm).

***Advantage of ozone:***

ozone is essential to the sustaining of both plant and mammalian life. It is the presence of ozone in the atmosphere that shields the Earth's surface from harmful solar UV radiation through its ability to absorb all solar radiation with wavelengths  $< 293$  nm so ozone has a strong *absorption band* between 210 and 300 nm.

***Disadvantage of ozone***

1. This ozone near the surface is poisonous in itself
2. Reacts with olefins (carbon compounds with carbon-carbon double bonds; they are present in car exhausts) such as ethylene ( $\text{H}_2\text{C}=\text{CH}_2$ ). These irritate the eyes and nose and cause respiratory problems.

**Ozone hole**

In 1985 it was discovered a sharp reduction in ozone concentrations above Antarctica; this was soon termed the *ozone hole*. Satellite monitoring of the ozone hole has shown that it is expanding and its depth increasing.

The uncontrolled release of the chlorofluorocarbons (CFCs) used in refrigerators,  $\text{CO}_2$ ,  $\text{CH}_4$  and aerosol cans into the terrestrial atmosphere would lead to the catalytic destruction of ozone.

## **Electromagnetic Radiation**

The electromagnetic force is one of the four fundamental forces, the others being the gravitational force, the strong nuclear force, and the weak interaction. The electromagnetic force dominates on the scale of atoms and molecules, determining the chemical properties of the elements and compounds, the chemical reactions occurring on the planet, and the mechanical, thermal, electrical, and optical properties of materials.

Electromagnetic radiation is emitted in the form of continuous spectra by accelerated charges and in the form of discrete or band spectra by atoms, molecules, and nuclei, or by electrons in solids.

Emission and absorption processes related to discrete spectra are described by quantum mechanics and the emitted radiation from emitting atom or molecule. For this reason spectroscopy is an invaluable tool to identify the presence of even small amounts of different chemicals, and spectroscopic techniques are widely used as tools in environmental physics to monitor, for example, the presence and abundance of pollutants, greenhouse gases, and of gases destroying the ozone layer.

### **The Electromagnetic Spectrum**

Electromagnetic waves cover a semi-infinite range of frequencies and wavelengths ranging from low-frequency (long wavelength) radio waves to the infrared, to the rather narrow optical band that we call “light” in everyday language, to the ultraviolet, and to the X and  $\gamma$  radiation corresponding to the highest frequencies. Electromagnetic waves travel at the speed of light, reflect, refract, diffract, and scatter, and these phenomena are frequency-dependent. The color of objects is explained by selective absorption and scattering.

Many of the following exercises focus on the propagation of electromagnetic waves through an absorbing medium.

At the low-frequency end of the spectrum there are extremely long waves (usually classified as noise) with wavelengths  $\lambda > 10^3$  m; then, in order of decreasing wavelength, corresponding to increasing frequency and energy, there are:

- radio waves with  $0.1\text{m} < \lambda < 10^3$  m
- microwaves with  $10^{-4}$  m  $< \lambda < 0.1$ m
- infrared radiation with  $7 \times 10^{-7}$  m  $< \lambda < 10^{-4}$  m
- visible light with  $4 \times 10^{-7}$  m  $< \lambda < 7 \times 10^{-7}$  m = 700 nm
- ultraviolet light with  $10^{-8}$  m  $< \lambda < 4 \times 10^{-7}$  m = 400 nm
- X-rays with  $10^{-11}$  m  $< \lambda < 10^{-8}$  m = 10 nm = 100 Å

—  $\gamma$ -rays with  $\lambda < 10^{-11}\text{m} = 10^{-2}\text{ nm} = 0.1^\circ\text{A}$ .

The energy of electromagnetic radiation is often measured in eV and the inverse wavelength in  $\text{cm}^{-1}$ . To prove that  $1\text{ cm}^{-1}$  is equivalent to  $1.24 \times 10^{-4}\text{ eV}$ , the relation between frequency  $\nu$  and wavelength  $\lambda$  of electromagnetic radiation is:

$$c = \lambda\nu$$

where:

$c$  = the speed of light in vacuum, combined with the relation between energy and frequency of a photon

$$E = h\nu$$

yields

$$E = hc/\lambda$$

If  $\lambda = 1\text{ cm}$ ,

$$\begin{aligned} E &= \frac{hc}{\lambda} = \frac{(6.625 \cdot 10^{-34}\text{ J} \cdot \text{s}) \cdot (2.998 \cdot 10^8\text{ m/s})}{1.00 \cdot 10^{-2}\text{ m}} = 1.986 \cdot 10^{-23}\text{ J} \\ &= 1.24 \cdot 10^{-4}\text{ eV}, \end{aligned}$$

where the conversion factor  $1\text{ eV} = 1.60 \times 10^{-19}\text{ J}$  is used.

### Propagation of electromagnetic radiation

The propagation of electromagnetic radiation in a medium is accompanied by absorption, which is differential. Absorption depends on the frequency of the radiation because of the quantum nature of atoms, molecules, and solids that resonate and exchange photons only in correspondence with selected frequencies determined by definite differences between different energy levels of the system.

*Intensity:*

Intensity of radiation is another name for the flux density of electromagnetic energy.

## Greenhouse Effect and Global Warming

Global warming is one of the most intensively studied aspects of modern environmental physics. The injection of greenhouse gases, mainly CO<sub>2</sub>, in the atmosphere since the beginning of the Industrial Revolution has created a sort of blanket that allows short-wavelength radiation to reach the surface of the Earth and traps longer-wavelength infrared radiation re-radiated by the Earth that would normally escape to outer space. The long-term effect is a global warming of the planet. While such a trend is actually being observed, it is not clear whether it is caused by manmade emissions or by natural causes.

(1) Describe the greenhouse effect in a farm greenhouse. What is the main difference between a greenhouse and the atmosphere?

*Solution*

In a greenhouse, short wavelength radiation in the visible band (wavelengths  $400\text{nm} < \lambda < 700\text{ nm}$ ) enters through the glass walls and is absorbed by the plants contained in it. Electromagnetic radiation is then emitted by the plants at shorter wavelengths in the infrared ( $700\text{ nm} < \lambda < 0.1\text{ mm}$ ). The glass of the walls is transparent to shorter wavelengths in the visible band and is opaque to the longer wavelengths re-radiated in the infrared by the plants—infrared radiation is therefore trapped inside the greenhouse. The main difference between the Earth's atmosphere and a greenhouse is that infrared radiation escapes from the Earth at night, while it cannot escape from the enclosed space of a greenhouse.

(2) Absorption of ultraviolet light in the atmosphere is described by the Lambert–Beer–Bouguer law. What would happen to the intensity of *UV* radiation on the surface of the Earth if the optical density decreased by one unit?

*Solution*

The Lambert–Beer–Bouguer law yields the intensity of *UV* radiation reaching the surface of the Earth

$$I = I_0 \cdot 10^{-\tau} \quad (16)$$

where  $\tau$  is the optical density. If  $\tau$  decreases by one ( $\tau$  is dimensionless), the intensity  $I$  increases by 10 units:

$$I \longrightarrow I_0 10^{-(\tau-1)} = 10 I_0 10^{-\tau}.$$

(3) The optical density from outer space to a point  $P$  in the atmosphere located below the ozone layer is  $\tau = 1$ . Assume that the ozone concentration drops by 10% and compute the ratio of intensities of UV-B radiation at  $P$  before and after the change of the  $O_3$  concentration.

#### *Solution*

The optical density to a generic point in the atmosphere is  $\tau = \varepsilon C z$ , where  $\varepsilon$  is the molar extinction coefficient,  $C$  is the concentration of ozone responsible for absorbing UV-B radiation, and  $z$  is the distance traveled by the UV-B rays. When the concentration of ozone undergoes the change  $C \rightarrow C' = 0.9C$  the optical density  $\tau = \varepsilon C z$  changes according to  $\tau \rightarrow \tau' = 0.9 \tau$ . Before the drop in  $C$  the intensity of UV-B is given by the Lambert–Beer–Bouguer law,  $I = I_0 \cdot 10^{-\tau}$ ; after  $C$  drops, the intensity is  $I' = I_0 \cdot 10^{-0.9 \tau}$ . The ratio of intensities is

$$\frac{I'}{I} = \frac{10^{-0.9\tau}}{10^{-\tau}} = 10^{0.1\tau}.$$

At point  $P$ , it is  $\tau = 1$  before the change and  $I'/I = 10^{0.1} = 1.259$ , thus a 10% change in the concentration of atmospheric ozone leads to a 26% change in the intensity of UV-B radiation. Since biomolecules and human tissues are very sensitive to UV-B radiation, a 26% increase in its intensity would have serious consequences on the incidence of skin cancer.

(4) When the concentration of greenhouse gases in the atmosphere increases,  $C_0 \rightarrow C$ , the temperature rises accordingly (*radiative forcing*) to compensate for the

decreased flux of infrared radiation leaving the atmosphere. Greenhouse gases are measured by their equivalent  $\text{CO}_2$  concentration. Two different models of radiative forcing found in the literature predict the temperature variations

$$\Delta T_1 = \tau \ln \left( \frac{C}{C_0} \right)$$

and

$$\Delta T_2 = \tau \frac{\Delta C}{C_0},$$

where  $\Delta C \equiv C - C_0$  and  $\tau = 6.1 \text{ K}$ . From 1850 to 1990 during the late Industrial Revolution, the value of  $C$  rose from 285 ppm to 360 ppm. Compare the predictions of the two models for the corresponding temperature change. Derive the second model from the first. What order of approximation in powers of  $\Delta C/C_0$  is needed in order to reach agreement to two significant figures between the two models?

*Solution*

In the first model of radiative forcing

$$\Delta T_1 = (6.1 \text{ K}) \ln \left( \frac{360 \text{ ppm}}{285 \text{ ppm}} \right) = 1.4 \text{ K},$$

2.17

while in the second model

$$\Delta T_2 = (6.1 \text{ K}) \frac{360 \text{ ppm} - 285 \text{ ppm}}{285 \text{ ppm}} = 1.6 \text{ K}.$$

2.61

The disagreement between the predictions of the two models is

$$\frac{\Delta T_2 - \Delta T_1}{\Delta T_2} = 13\%.$$

17%

The second model is nothing but the linear approximation of the first one and is only adequate for small values of  $\Delta C/C_0$ . By using the series

$$\ln(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \dots$$

for  $|x| < 1$ , one computes the corrections to the following orders:

$$\begin{aligned} \Delta T &= \tau \ln \frac{C}{C_0} = \tau \ln \left( 1 + \frac{\Delta C}{C_0} \right) \\ &= \tau \left[ \frac{\Delta C}{C_0} - \frac{1}{2} \left( \frac{\Delta C}{C_0} \right)^2 + \frac{1}{3} \left( \frac{\Delta C}{C_0} \right)^3 - \frac{1}{4} \left( \frac{\Delta C}{C_0} \right)^4 + \dots \right]; \end{aligned}$$

to first order, one recovers the second model of radiative forcing,  $\Delta T = \tau \Delta C / C_0$ .

The leading order correction yields

$$\begin{aligned} \Delta T &= (6.1 \text{ K}) \left[ \left( \frac{360 \text{ ppm} - 285 \text{ ppm}}{285 \text{ ppm}} \right) \right. \\ &\quad \left. - \frac{1}{2} \left( \frac{360 \text{ ppm} - 285 \text{ ppm}}{285 \text{ ppm}} \right)^2 \right] = 1.4 \text{ K}. \end{aligned}$$

The second-order correction is necessary since  $\Delta C / C_0 \approx 0.263$  is not a very small number and the linear approximation is not accurate. To the relevant accuracy (two significant figures) the second-order approximation agrees with the exact model.

(5) Assume that the heat flux  $F$  radiated by the Earth in space suddenly decreases due to the greenhouse effect, caused by an abrupt increase in the concentration of greenhouse gases in the atmosphere. Since the Earth is in thermal equilibrium with outer space its surface temperature  $T_s$  must increase to compensate for the decrease of  $F$ , according to the Stefan–Boltzmann law. This *radiative forcing* is described by

$$\Delta T_s \equiv T_s(t) - T_0 = G \Delta F,$$

where  $T_0$  is the surface temperature before the change,  $\Delta F$  is the magnitude of the variation of  $F$ , and  $G$  is a *gain function*, which in the linear approximation is

simply  $\partial T_s / \partial (\Delta F) |_{\Delta F=0}$ . Refine this model by taking into account the thermal inertia of the oceans covering 70% of the Earth's surface. Let  $c m$  be the heat capacity of the top layer of the oceans interested by global warming ( $m$  is its mass and  $c$  is the specific heat of water); derive a differential equation for the surface temperature  $T_s(t)$  and find its solution.

### Solution

The heat flux (energy passing per unit time through the unit area normal to the direction of propagation) is  $F = dQ/dt dS$  and the magnitude of its variation due to the greenhouse effect is  $\Delta F$ . We obtain

$$\Delta F = \frac{d(\Delta Q)}{dt dS} + \frac{\Delta T_s}{G},$$

where  $\Delta Q$  is the difference between the heat lost by the Earth's surface after and before the change in the greenhouse gases concentration. Since  $\Delta Q = cm\Delta T_s$ , it is straightforward to conclude that  $T_s$  obeys the differential equation

$$\frac{d(\Delta T_s)}{dt} + \frac{\Delta T_s}{\gamma G} = \frac{\Delta F}{\gamma},$$

where  $\gamma \equiv d(cm)/dS$  is the heat capacity of the oceans per unit area. The general solution of the homogeneous equation associated with Eq. (4) is

$$\Delta T_s(t) = A e^{-t/\tau},$$

where  $\tau \equiv \gamma G$  is a time scale. A particular solution of the inhomogeneous equation (4) is

$$\Delta T_s = G \Delta F,$$

and therefore the general solution of Eq. (4) is

$$T_s(t) = T_0 + A e^{-t/\tau} + G \Delta F.$$

The integration constant  $A$  is determined by the initial condition  $T_s(0) = T_0$ , which yields  $A = -G\Delta F$ , and therefore

$$T_s(t) = T_0 + G \Delta F \left(1 - e^{-t/\tau}\right).$$

The solution goes to its asymptotic value  $T_0 + G\Delta F$  as  $t \rightarrow +\infty$ . In practice  $T_s$  reaches 90% of this value after a time  $t = 2.3 \tau$ . The effect of the thermal inertia of the oceans is to introduce a time lag in the global warming of the planet—without the oceans we would have the constant solution  $T_0 + G\Delta F$ . The time scale  $\tau$  is estimated to be between 50 and 100 years. In order or magnitude we have

$$\tau = \gamma G = \frac{d(cm)}{dS} G \simeq \frac{cmG}{0.7 \cdot 4\pi R_E^2} = \frac{c\rho (0.7 \cdot 4\pi R_E^2) hG}{0.7 \cdot 4\pi R_E^2} = c\rho hG,$$

where  $R_E$  is the Earth's radius and  $h$  the depth of the top layer of the oceans. Realistic values are  $G = 0.7 \text{ }^\circ\text{C} \cdot \text{s} \cdot \text{m}^2/\text{J}$  and  $h = 1 \text{ km}$ , yielding

$$\begin{aligned} \tau &\sim \left(4187 \frac{\text{J}}{\text{kg} \cdot (^\circ\text{C})}\right) \left(1.0 \cdot 10^3 \frac{\text{kg}}{\text{m}^3}\right) (10^3 \text{ m}) \left(0.7 \frac{^\circ\text{C} \cdot \text{s} \cdot \text{m}^2}{\text{J}}\right) \\ &\sim 3 \cdot 10^9 \text{ s} \sim 93 \text{ years.} \end{aligned}$$

## Wind

### Physics of wind Creation

The atmosphere is a gigantic heat engine. The radiation from the Sun causes convection both on a local scale and on a global scale. The difference in energy delivered at the equator and the poles creates the pressure differences that drive the major wind systems in the Earth's atmosphere. Winds are masses of air in motion. An air mass has a reasonably precise meaning in meteorology. This is a large volume of air (covering millions of square kilometers) that has reasonably constant pressure and humidity. Thus, the air mass will determine the overall weather of a region (although not the local microclimate). They come

from the extensive regions of high pressure that characterize some of the areas of the Earth, the subtropical oceans (throughout the year) and the mid and high latitude continents (mainly in winter). Air spirals out from these high-pressure areas (anticyclones) to create the wind systems of the planet. The boundaries that separate air masses are called fronts. Hereabouts a cold front is the leading edge of a cold air mass and brings rain. The warm moist air of the tropical maritime mass it is replacing is forced upwards, cools and water precipitates out.

### **Principal forces acting on air masses**

If we want to understand why the winds occur, it is necessary to consider the forces that act on the air masses in the atmosphere. To any observer stationary with respect to the surface of the Earth, there are four forces acting on a parcel of air in the atmosphere:

- Gravitational,
- Pressure gradient,
- Coriolis fictional force, and
- Frictional force.

#### *Gravitational force:*

Due to the large mass of the Earth, the gravitational force is one of the strongest forces acting on the air parcel and is directed towards the centre of the Earth

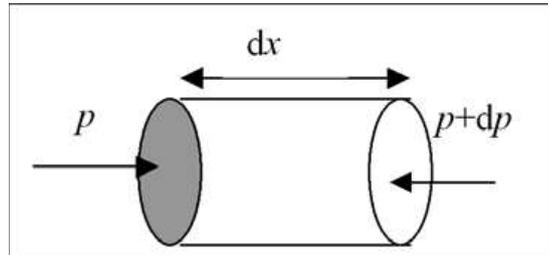
$$F_g = g\rho\Delta V$$

where  $g$  is the gravitational acceleration constant (more or less constant through the troposphere),  $\rho$  is the density of air, and  $\Delta V$  is the volume of the parcel.

#### *Pressure gradient:*

The pressure at the surface of an air parcel is the normal component of the force exerted by its surroundings on a unit area of surface. This force is always

directed towards the parcel. The parcel will experience a net force if there is a difference between the pressures on the surfaces at different sides.



Consider the above diagram where the shaded cross-section has area  $dA$ . The net force on the parcel due to the pressure difference is

$$F_p = p dA - (p + dp) dA = - dp dA$$

If  $\rho$  is the density of air, then the force per unit mass (i.e. the acceleration) is given by

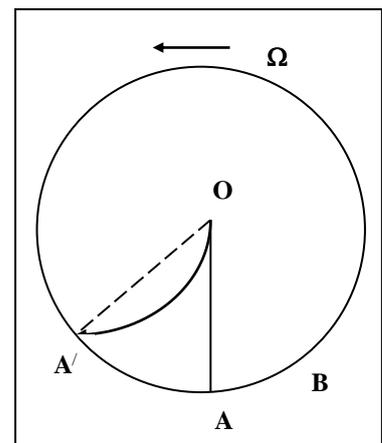
$$\frac{F_p}{\rho dA dx} = - \frac{1}{\rho} \frac{dP}{dx} = - \frac{1}{\rho} \frac{dP}{dx}$$

Taking the limit in the usual way and generalising to three dimensions, we get

$$\mathbf{F}_p = - \frac{1}{\rho} \nabla P$$

*Coriolis force:*

Consider the above diagram which represents a region around the North Pole (O) such that we can consider it to be a rotating disc. An air parcel starts to move horizontally away from the pole towards a point A. If no forces act on this parcel, by Newton's laws it will follow a direct path OA. However, the disc is also rotating with an angular velocity,  $\Omega$ , and so it will



follow the curved line OA' with respect to the disc. The disc has moved on, and so the point A is at B by the time the parcel of air reached the edge. To an

observer rotating with the Earth, it looks as though the parcel is deflected by a force away from A towards A'. This fictitious force is called the Coriolis force. The Earth is a sphere and not a disc, which means that we should use the full vector notation, but the principles are the same. We must calculate the vector product between the rotation vector  $\vec{\Omega}$  (directly out of the plane for the disc) and the velocity vector,  $\vec{v}_g$ .

Applying this to the Earth, if we consider an air parcel with velocity  $\mathbf{vg}$ , and the angular velocity vector of the earth is  $\vec{\Omega}$ , then the Coriolis force per unit mass is given by

$$\vec{F} = -2\vec{\Omega} \times \vec{v}_g$$

The point where the Coriolis effect balances the pressure gradient is called the geostrophic balance and the resulting wind called the *geostrophic wind*.

### The frictional force

There exists considerable frictional force between the atmosphere and the earth's surface (for example due to mountains and hills. Lines of tall trees are planted to act as wind breaks and protect crops). Frictional forces are difficult to treat properly. The mechanism is essentially a form of viscosity (at low altitudes) and small-scale eddy mixing processes at higher altitudes. The layer where the frictional force is important is known as the *planetary boundary layer*. The thickness of the layer is very variable; from a few hundred metres in still air at night to 4-5km over a hot surface with strong convection.

This introduces the question of how the wind speed varies with height which is obviously closely tied to the question of how atmospheric pressure varies with height. We considered this question when we looked at the structure of the atmosphere. Its connection to the wind speed can be seen through the following argument.

## Energy and the environment

To date, most energy has been derived from fossil fuels; gas, oil and coal with a little wood and biowaste. With industrialization, the rate of energy use has increased 30-fold. At first, the main fossil fuel was coal, since 1950 the major growth has been in the use of oil.

Coal usage has decreased by about 25% and gas increased by about the same. The total figure for *primary* energy has remained (roughly) constant. Countries vary, but the pattern of end-use is reasonably typical of an industrial nation. About 40% of the energy demand is for low-temperature heating and space cooling; about 20% for high-temperature heating (i.e. above the boiling point of water; mainly industrial) . About 30% is used in transport. Only about 5-10% is used for activities that require electricity (i.e. lighting, electrolysis, electronic equipment and so on. In developing countries a greater percentage of energy use goes in cooking and less in space heating but otherwise the distribution is similar. In both developing and developed countries, the average spend on energy per person is about 5% of annual income.

### Energy resources:

#### 1- Fossil fuels:

These are, and are likely to remain, the major source of energy for many years despite the increasing concerns about global warming. Thermal power stations (be they fossil or nuclear) have a heating element, a boiler and a turbine. The *Carnot efficiency*,  $\eta$ , of a heat engine is given by

$$\eta = (T_h - T_c) / T_h$$

where  $T_h$  is the temperature of the hot reservoir and  $T_c$  is the temperature of the cold reservoir. The cold reservoir is the environment (usually a river) and so, in

practice, has a temperature of about  $15^{\circ}\text{C}$  ( $288\text{K}$ ). The hot reservoir can get up to  $600\text{-}700^{\circ}\text{C}$  ( $900\text{K}$  or thereabouts). This gives Carnot efficiencies of the order of 70%. Real power stations are not reversible Carnot engines and cannot reach efficiencies of anything like this. A total efficiency of 42% would be reckoned to be good for a normal coal-fired power-station.

One device to improve the utilization of the system is to construct a combined heat and power generator (CHP). The overall efficiency of this,  $\eta_{\text{CHP}}$  is defined as:

$$\eta_{\text{CHP}} = \frac{\text{net power output} + \text{heat recovered}}{\text{energy input}} \times 100$$

The gains are obvious (about 2/3 of the waste heat can be recovered). It works best for a fixed balance of heat and power (1:1 in many cases). In practical situations the ratio required may vary (For example, who needs domestic space heating in summer?). There is significant extra investment required in plant and heat pipelines (also there is a need for backup). If the CHP system is also a district heating scheme there may be problems of noise and pollution since the plant must be close to the district it serves.

## 2- Nuclear power:

In principle, three methods of obtaining power from nuclear energy have been considered; *thermal reactors* (which obtain energy from the fission of isotopes of uranium or thorium), *breeder reactors* (which in addition to doing this also convert the natural uranium isotope  $\text{U}^{238}$  to a fissile isotope of plutonium,  $\text{Pu}^{239}$ ) and *fusion reactors* (which use the reaction  ${}^2\text{D}_1 + {}^3\text{T}_1 \rightarrow {}^4\text{He}_2 + {}^1\text{n}_0 + \text{energy}$ ; the tritium being obtained from lithium by neutron bombardment).

## Renewable resources:

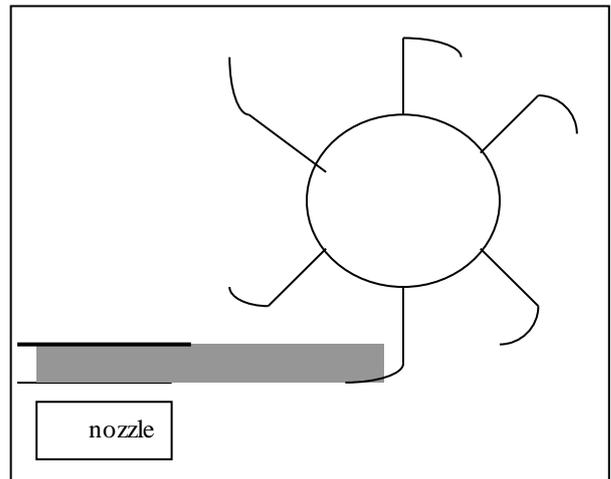
These amount, in the end, to harnessing solar energy directly or indirectly (with the exception of tidal power which in the end harnesses the rotational energy of the earth and geothermal which harnesses the internal heat of the earth). In principle there is a lot of solar energy; about 18000TW falls on the earth. The basic problem is collecting it; the energy density is very low. Current usage is as follows:

1. Hydroelectric (6% of global energy requirements)
2. Biomass (i.e. wood-burning) 1.5% of global requirements
3. Tidal, solar, geothermal, wind *together* provide about 0.5% of global requirements

In other words, only hydroelectric is making a significant contribution. We will now consider each source in turn.

### 1- Hydro-electric power:

The main advantage of hydro-electric power is that the energy density is high. The basic method is simple. Water passes from a dam down a tube and through a turbine. The idea is to convert the potential energy of the water first into kinetic and then into electrical energy. If  $\rho$  is the density of water,  $Q$  is the flow-rate then  $P_0$ , the maximum power available to be generated is given by



$$P_0 = \rho ghQ \quad (1)$$

where  $h$  is the height drop. Equivalently, one can look at the problem from the point of view of the kinetic energy; if the velocity of the water is  $u$ , the power available is  $\rho Qu^2/2$ , one kind of turbine is the *Pelton impulse turbine*. Consider

the case where the water from the jet is hitting the bottom cup. If the velocity of the cup is  $u_t$  and the velocity of the jet is  $u_j$ , then if we take the ideal case where the cup deflects the stream by  $180^\circ$  and there is no friction to worry about then, with respect to the frame of reference of the cup, the speed of the water jet is  $(u_j - u_t)$  both before and after the water hits the cup. (The direction of course is reversed). This is also the *change* of velocity seen in the laboratory frame. Thus the change of momentum of the fluid (and thus the force exerted on the cup) is

$$F = 2\rho Q(u_j - u_t) \quad (2)$$

to the right in the diagram. The power transferred is:

$$P = Fu_t = 2\rho Q(u_j - u_t)u_t \quad (3)$$

This is a maximum for  $u_j / u_t = 0.5$  in which case the power output is the kinetic energy of the water in the jet; i.e. the turbine is 100% efficient. Real efficiencies vary from 50% (for small units) to 90% for large commercial systems.

## **2- Tidal power:**

This is similar to hydro-electric power *except* that it is not a continuous source. In principle there is a lot of energy available but there is the problem both of energy density (how many estuaries are suitable) and of environmental problems. The largest tidal installation (and has been for many years) is at La Rance (France) with a capacity of 240MW. The basic idea is to trap the tide behind a barrier and let the water out through a turbine at low tide. If the tidal range is  $R$  and the estuary area is  $A$ , then the mass of water trapped behind the barrier is  $\rho AR$  and the centre of gravity is  $R/2$  above the low tide level. The maximum energy per tide is therefore  $(\rho AR)g(R/2)$ . Averaged over a tidal period of  $\tau$ , this gives a mean power available of

$$\bar{P} = \rho A R^2 g / 2 \tau$$

### 3- Wind power:

'wind turbines' consist of a two or three bladed propeller (33m in diameter). The rate of power generated in a wind speed of Beaufort scale 6 (strong breeze; about 30mph) is 300kW. In the U.K. the average wind speed for usable sites is about 17mph and the output about 100kW. Hence the need for a wind farm.

Again, the basic physics is simple. The kinetic energy in a unit volume of air is given by  $\rho u^2/2$  where  $\rho$  is the air density and  $u$  the wind velocity. The volume of air passing cross-section  $A$  perpendicular to the wind velocity in time  $t$  is given by  $uAt$  (or  $u$  per unit cross-section per unit time). If the angle of the wind direction to the normal of the cross section defined by the wind turbine is  $\beta$ , the volume of air passing through unit area of the turbine cross-section is  $u \cos\beta$ . Hence the maximum power per unit area

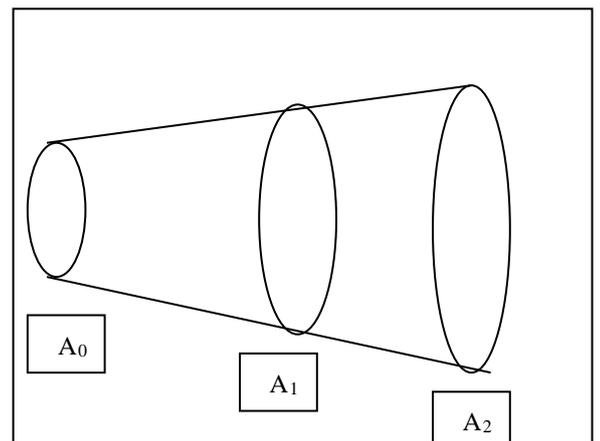
$$P_0/A = (\rho u^3 \cos \beta)/2 \quad (4)$$

In principle, the maximum power available occurs when  $\cos \beta = 1$  and then

$$P_0/A = \rho u^3 / 2 \quad (5)$$

In practice, only a small fraction of this is really available and the right-hand side of (5) is multiplied by a coefficient  $C_p$ , the *coefficient of performance*. The basic point of (5), that there is a power law dependence on the wind velocity remains. Effective wind turbines need high wind velocities.

Area  $A_1$  is the area swept out by the rotor. Areas  $A_0$  and  $A_2$  enclose the stream of constant mass passing through  $A_1$ . The area  $A_0$  is far enough upstream that it is not affected by the rotor. The area  $A_2$  is at the position of



minimum wind speed downstream (before the windfront reforms and the effect of the rotor is washed out). The force on the turbine is the reduction in momentum from the flow of air. If the rate of flow of mass is  $Q$ , then

$$F = Q (u_0 - u_2) \quad (6)$$

If the air is moving with velocity  $u_1$  as it passes the turbine, then the power extracted must be

$$P = Fu_1 = Q (u_0 - u_2) u_1 \quad (7)$$

and the loss of energy per unit time is the power extracted from the wind i.e.

$$P = Q (u_0^2 - u_2^2)/2 \quad (8)$$

For a 100% efficient turbine, these can be equated, which gives

$$u_1 = (u_0 + u_2) / 2 \quad (9)$$

Thus the air speed through the rotor must be at least half the unperturbed wind speed.

The mass of air flowing through the disk per unit time is obviously  $Q = \rho A_1 u_1$ , so the power must be

$$P = \rho A_1 u_1^2 (u_0 - u_2) \quad (10)$$

#### **4- Wave power:**

In principle, large amounts of energy can be obtained from waves. Most devices are designed to extract energy from deep water waves, where the mean depth of the seabed,  $D$ , is greater than half the wavelength of the wave,  $\lambda$ . The basic properties of such waves are:

- the surface waves are sine waves of irregular phase and direction
- the motion of any particle of water is circular; the waves move but the water does not.

- water on the surface stays on the surface.
- the amplitude of the motions of the water particles decreases exponentially with depth.
- the amplitude of the surface wave is independent of the wavelength or velocity.
- a wave breaks when the slope of the surface is about 1 in 7.

The power in a wave comes from the change in potential energy of the water as it rotates on the circular paths beneath the surface. It can be shown that the power carried forward by a wave is given by

$$P = \rho g^2 A^2 T / 8 \pi \quad (1)$$

where  $A$  is the amplitude of the wave at the surface and  $T$  is the period of the wave. Two devices intended to extract this power are the *Salter duck* and the *oscillating column*. The Salter duck consists of a cone that oscillates with the waves and is connected to a rotary pump that drives a generator. The oscillating column uses the wave to drive a trapped air column past a turbine. A number of prototypes have been tried (on about 1/10 scale in the U.K. in the early 1980's) but the economics of the power generation is not yet good enough for a full commercial trial.

### **5- Biomass (as fuel):**

Second in importance to hydro (at present) is the use of biomass as a renewable fuel. The term covers domestic, industrial and agricultural dry waste material, wet waste material and crops. The U.K. generates 30 million tonnes of solid waste per year (0.5 ton each). If all that could be incinerated was incinerated, this would generate 1.7GW (5% of U.K. requirements). The essential difference between this and fossil fuels is that the biomass cycle is a true cycle provided that for each plant used as fuel a replacement is planted. Examples of biofuels include

- *Gaseous biofuels* are used for (a) heating and cooking, and (b) in engines for

electricity and heat generation, and occasionally for transport. Examples include *biogas* ( $\text{CH}_4$  and  $\text{CO}_2$ ) from anaerobic digestion of plant and animal wastes, and *Producer gas* ( $\text{CO}$  and  $\text{H}_2$ ) from gasification of plants, wood and wastes.

- *Liquid biofuels* are used mainly for transport fuels. Examples are: oils from crop seeds (e.g. rape, sunflower), esters produced from such oil, ethanol from fermentation and distillation, and methanol from acidification and distillation of woody crops.
- *Solid biofuels* : Examples are: wood from plantations, forest cuttings, timber yards and other wastes, charcoal from pyrolysis, and refuse derived fuels, e.g. compressed pellets.

A major user of biomass is Brazil; the source being waste from the sugar-cane industry. Bagasse (residue after crushing the cane) and barbojo (leaves of the cane). Perhaps 67% of the 80 sugar-cane producing countries can use this as fuel.

### **6- Solar power:**

The simplest way of making use of energy from the sun is to turn it into heat. A black surface directly facing full sunlight can absorb  $1\text{kW} / \text{m}^2$ . The Southern USA has 350MW plants based on this idea.

Solar energy can be either *direct* or *diffuse*. Only direct radiation can be concentrated. The energy received from the sun at a given place depends on the latitude, time of day and season. If you wish to maximize the solar energy absorbed on a surface, you must slant it so that its normal points at the sun. For best results, the orientation should change during the day, and even correcting the angle from day to day to allow for the declination with the seasons. It is usually not worth the cost to do this. It is enough to set the surface to face the sun at noon and fix the angle with the horizontal to this. In the U.K. the relevant angle is  $30^\circ$  from the horizontal for solar panels. For some applications a

*concentrator* can be used. In principle, a paraboloid is the the most efficient, but a parabolic trough is much easier to build.

### *Solar photovoltaic:*

Solar radiation can be converted directly into electricity by solar photovoltaic cells. (Examples of use include watches/calculators, solar arrays for space craft). Practical cells made of amorphous silicon. Efficiencies are 10-20%. Hence a panel of cells 1m<sup>2</sup> facing full sunlight will give 100-200W. i.e. large area required for significant amounts of power. In 1990, world capacity was about 50MW. To meet WEC (World Energy Council) projections we would need 1000 times this amount by 2020. Only a few 'trials' of large-scale power production; e.g. Sri Lanka; 1.3kW solar array backed by 2200A-hr battery to provide lighting and refrigeration for vaccines in a hospital.

## **Noise pollution**

Noise is not often thought of as a *pollutant*, but unwanted sound (noise) can seriously degrade the quantity of life. The acceptance of noise by people obviously depends on the individual, but it has been legislated on levels of sound acceptable to the community. The level of noise deemed to be acceptable is dependent upon:

- *The type of environment:* acceptable levels of surroundings noise are affected by the type of activity. A library, for example, has different requirements to those on a factory floor.
- *Frequency structure:* different noises contain different frequencies and some frequencies are found to be more annoying than lower frequency rumbles.
- *Duration:* a short period of high level noise is less likely to annoy than a long

period.

Different people have different hearing sensitivities, but average values can be measured and provide a map of the sound that the human ear can detect. The *threshold of hearing* is the weakest sound that the average human hearing can detect. The threshold varies slightly with the individual, but it is remarkably low. There is also high threshold, the *threshold of pain*, which is the strongest sound that the human ear can tolerate.

Absolute measurements of sound intensity can be expressed in either  $\text{Wm}^{-2}$  or in sound pressure, Pa, but such units do not correspond directly to the way in which the human ear responds to sound levels. Since the human ear has a non-linear response to the energy content of sound, a logarithmic scale is used to describe the response of the ear. It is converted to *sound level* measured in decibels, dB.

$$L = 10 \log(I/I_0)$$

$$\text{or} \quad L = 20 \log(p/p_0)$$

where  $I_0 = 10^{-12} \text{ Wm}^{-2}$  and  $p_0 = 2 \cdot 10^{-5} \text{ Pa}$  are the values for the threshold of hearing,  $I$  and  $p$  the intensity and pressure of the sound being measured.

### **Hearing loss:**

Sound level meters usually have special networks built into them so that the meter's response is more nearly like that of the ear. The most commonly used weighting network is called "A", and matches the response of the ear moderate levels rather well. When a weighting network is used, the sound level reported as "dBA".

sound level meter can either have a "fast" response, or a "slow" response which averages over about a 1/2 second period. Most often the unit used is "dBA-slow". The population at risk with regards to noise- induced hearing loss may be greater than any other hazard in the work environment. Legislation setting maximum permissible sound levels, the main law is the Occupational

Safety and Health Act (OSHA) of 1970. The current limit permitted depends on the exposure time, as shown in the following table:

hours/ day	dBA-slow
8	90
4	95
2	100
1	105
1/2	110
1/4	115

At no time can the noise level exceed 115 dBA. Since loud, very short duration noises do not show up on the slow scale, there is a separate limit of 140 dB peak for impact noises.

It is important to note that present data show that the standards of the above table will still cause 20% to 30% more hearing impairment to workers after 20 years than for general population. The standards would have to be dropped to 80 dBA for 8 hours to keep hearing loss minimal.

### **Adding Intensity Levels:**

*Example:*

Suppose there are two sources of sound close to each other, each with a sound intensity level,  $L_I$ , of 80 dB. What is the total sound intensity level?

*Solution:*

Intensity levels do not add linearly, as intensities do.

$$L = 10 \log(I/I_0)$$

$$\frac{L_1}{10} = \log\left(\frac{I}{I_0}\right)$$

If both sides of the equation are raised to the power 10, recalling that  $10^{\log x} = x$ , where  $x$  is any quantity,

$$10^{(L_I/10)} = \left( \frac{I}{I_o} \right)$$

Then:

$$I_o 10^{(L_I/10)} = I$$

The sound intensity for each source is then:

$$I = 10^{-12} \frac{\text{watt}}{\text{m}^2} \times 10^{(80/10)} = 10^{-4} \frac{\text{watt}}{\text{m}^2}$$

The sum of the two intensities is  $2 \times 10^{-4} \text{ watt /m}^2$ .

$$\begin{aligned} L_I &= 10 \log \left( \frac{2 \times 10^{-4}}{10^{-12}} \right) = 10 \log (2 \times 10^8) \\ &= 10 (\log 2 + \log 10^8) \\ &= 10 \times 8.3 \\ &= 83 \text{ dB} \end{aligned}$$

Although the intensity doubled, the intensity level went up by only 3 dB.

*Example:*

If one jet causes a sound level of 120 dB on take off, what is the sound level of three such jets taking off simultaneously?

*Solution:*

For one jet:  $L = 120 \text{ dB}$  gives us  $I = 1 \text{ Wm}^{-2}$ .

For three jets:  $I = 3 \text{ Wm}^{-2}$  giving  $L = 10 \log (3/10^{-12}) = 124.8 \text{ dB}$ .

### **Noise control:**

One can divide control techniques by the location where the control is applied:

*1- at the source:*

In many cases noise can be reduced considerably at the source. Machinery can be redesigned to reduce noise.

*2- along the transmission path:*

If the noise can not be stopped at the source, then attenuation along the path must be used. The way to reduce the transmission of sound is to isolate the source if possible.

3- *at the hearer:*

If nothing else can be done, the final line of defense against noise is ear plugs and acoustic ear mufflers. About 15 to 30 dB reduction is available by this method.

**Question:**

A washing machine generating 90 dB of noise is turned on at the same time as a ghetto-blaster generating 100 dB is on in the room. What is the total noise level in the room? (**Answer:** 100.4 dB).

## **Thermal Pollution**

Thermal pollution is the degradation of water quality by any process that changes ambient water temperature. A common cause of thermal pollution is the use of water as a coolant by power plants and industrial manufacturers. When water used as a coolant is returned to the natural environment at a higher temperature, the change in temperature (a) decreases oxygen supply, and (b) affects ecosystem composition.

Urban runoff-stormwater discharged to surface waters from roads and parking lots-can also be a source of elevated water temperatures. When a power plant first opens or shuts down for repair or other causes, fish and other organisms adapted to particular temperature range can be killed by the abrupt rise in water temperature known as 'thermal shock'.

### **Ecological effects - warm water**

Elevated temperature typically decreases the level of dissolved oxygen (DO) in water. The decrease in levels of DO can harm aquatic animals such as fish, amphibians and copepods.

Thermal pollution may also increase the metabolic rate of aquatic animals, as enzyme activity, resulting in these organisms consuming more food in a shorter time than if their environment were not changed.

An increased metabolic rate may result in fewer resources; the more adapted organisms moving in may have an advantage over organisms that are not used to the warmer temperature. As a result one has the problem of compromising food chains of the old and new environments. Biodiversity can be decreased as a result. It is known that temperature changes of even one to two degrees Celsius can cause significant changes in organism metabolism and other adverse cellular biology effects. Principal adverse changes can include rendering cell walls less permeable to necessary osmosis, coagulation of cell proteins, and alteration of enzyme metabolism. These cellular level effects can adversely affect mortality and reproduction.

Primary producers are affected by warm water because higher water temperature increases plant growth rates, resulting in a shorter lifespan and species overpopulation. This can cause an algae bloom which reduces oxygen levels.

A large increase in temperature can lead to the denaturing of life-supporting enzymes by breaking down hydrogen and disulphide bonds within the quaternary structure of the enzymes. Decreased enzyme activity in aquatic organisms can cause problems such as the inability to break down lipids, which leads to malnutrition.

In limited cases, warm water has little deleterious effect and may even lead to improved function of the receiving aquatic ecosystem. This phenomenon is seen especially in seasonal waters and is known as thermal enrichment. An extreme case is derived from the aggregational habits of the manatee, which often uses power plant discharge sites during winter. Projections suggest that manatee populations would decline upon the removal of these discharges.

**Ecological effects - cold water**

Releases of unnaturally cold water from reservoirs can dramatically change the fish and macroinvertebrate fauna of rivers, and reduce river productivity. In Australia, where many rivers have warmer temperature regimes, native fish species have been eliminated, and macroinvertebrate fauna have been drastically altered.

**Industrial wastewater**

Thermal pollution from industrial sources is generated mostly by power plants, petroleum refineries, pulp and paper mills, chemical plants, steel mills and smelters. Heated water from these sources may be controlled with:

- cooling ponds, man-made bodies of water designed for cooling by evaporation, convection, and radiation.
- cooling towers, which transfer waste heat to the atmosphere through evaporation and/or heat transfer.
- cogeneration, a process where waste heat is recycled for domestic and/or industrial heating purposes.

Some facilities use once-through cooling (OTC) systems which do not reduce temperature as effectively as the above systems. For example, the Potrero Generating Station in San Francisco, which uses OTC, discharges water to San Francisco Bay approximately 10°C (20°F) above the ambient bay temperature.

**Urban runoff**

During warm weather, urban runoff can have significant thermal impacts on small streams, as stormwater passes over hot parking lots, roads and sidewalks. Stormwater management facilities that absorb runoff or direct it into groundwater, such as bioretention systems and infiltration basins, can reduce these thermal effects. Retention basins tend to be less effective at reducing

temperature, as the water may be heated by the sun before being discharged to a receiving stream.