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Atmospheric Physics Lab Work

Evaporation

Abstract

In the first part of this experiment, the relationship between wind speed and evaporation is investigated. We measure the evaporation under idealized conditions using a small wind tunnel. We then compare our results from the experiment with calculated values for the evaporation over the sea.

In the second part of the experiment, we have a look at the wind chill effect. We demonstrate the influence of different wind velocities on the cooling rate.

Questions to be answered during the reading of the manual
(Will be discussed in a small tutorial ahead of the experiment)

Evaporation:

- What do you expect for the evaporation for increasing wind velocities?
- What should you get for the global evaporation/precipitation?

Wind Chill Effect:

- Is there a wind chill effect if the body has the same temperature as the environment?

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1. Equipment

- Wind tunnel
- Velocimeter
- Evaporimeter
- Psychrometer
- Watch: to bring along (with an accuracy of one second)
- Hot plate

2. Evaporation

2.1. Introduction

Water is transported from the surface of the Earth into the atmosphere by two distinct mechanisms: evaporation and transpiration.

Evaporation can be defined as the process where liquid water is transformed into a gaseous state. Evaporation can occur only when water is available. It also requires that the humidity of the atmosphere is less than the evaporating surface (at 100 % relative humidity there is no more evaporation). The evaporation process requires large amounts of energy. For example, the evaporation of one gram of water requires 600 calories of heat energy.

Transpiration is the process of water loss from plants through stomata. Stomata are small openings found on the underside of leaves that are connected to vascular plant tissues. In most plants, transpiration is a passive process largely controlled by the humidity of the atmosphere and the moisture content of the soil. Of the transpired water passing through a plant only 1 % is used in the growth process. Transpiration also transports nutrients from the soil into the roots and carries them to the various cells of the plant and is used to keep tissues from becoming overheated. Some dry environment plants do have the ability to open and close their stomata. This adaptation is necessary to limit the loss of water from plant tissues. Without this adaptation, these plants would not be able to survive under conditions of severe drought.

It is often difficult to distinguish between evaporation and transpiration. So we use a composite term evapotranspiration. The rate of evapotranspiration at any instant from the Earth's surface is controlled by four factors:

- Energy availability. The more energy available the greater the rate of evapotranspiration. It takes about 600 calories of heat energy to change 1 gram of liquid water into a water vapor.
- The humidity gradient away from the surface. The rate and quantity of water vapor entering into the atmosphere both become higher in drier air.
- The wind speed directly above the surface. Many of us have observed that our gardens need more watering on windy days compared to calm days when temperatures are

similar. This fact occurs because wind increases the potential for evapotranspiration. The process of evapotranspiration transports water vapor from ground or water surfaces to an adjacent shallow layer that is only a few centimeters thick. When this layer becomes saturated evapotranspiration stops. However, wind can remove this layer replacing it with drier air, which increases the potential for evapotranspiration.

- Water availability. Evapotranspiration cannot occur if water is not available.

On a global scale, most of the evapotranspiration of water on the Earth's surface occurs in the subtropical oceans. In these areas, high quantities of solar radiation provide the energy required to convert liquid water into a gas. Evapotranspiration generally exceeds precipitation on middle and high latitude landmass areas during the summer season. Once again, the greater availability of solar radiation during this time enhances the evapotranspiration process.

The average evapotranspiration for the northern hemisphere is around 944 mm/y. Together with the southern hemisphere, with an average evapotranspiration of 1064 mm/y, this results in a global evapotranspiration of 1004 mm/y. In the Western Pacific and Indian Ocean values up to 2 m/y have been observed.

2.2. Scientific basis

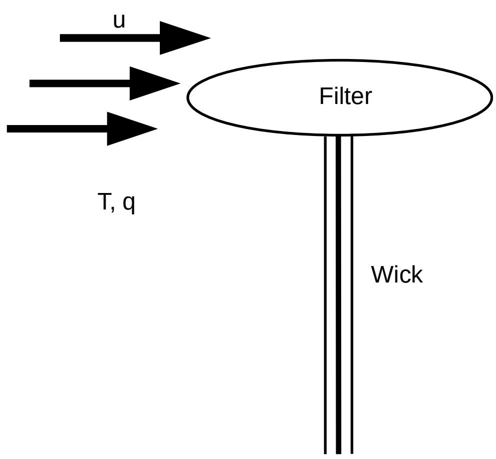

Figure 1: Evaporimeter

The evaporation is defined as follows:

$$E = \rho_w \frac{dV}{dt} \frac{1}{A} \quad (1)$$

with

ρ_w	=	water density [kg/m^3]
$\frac{dV}{dt}$	=	temporal volume change due to evaporation [m^3/s]
A	=	surface area [m^2]

For an infinitesimally small surface the evaporation is described as a function of the wind speed and water vapor gradient:

$$E = \alpha \langle u \rangle (e_s - e) \quad (2)$$

with

E	=	evaporation [kgm^2s^{-1}]
$<u>$	=	wind speed [m/s]
e	=	water vapor pressure in the atmosphere [Pa]
e_s	=	saturation vapor pressure for temperature T [Pa]
α	=	constant [s^2/m^2]

The water vapor pressure is defined as follows:

$$e = e_s - \tilde{A}\, p\,(T - T_w) \tag{3}$$

with

$\tilde{A}$	=	psychrometer constant 6.6e-4 K^{-1} for an air velocity of 2 m/s
e	=	water vapor pressure in the atmosphere [Pa]
e_s	=	saturation vapor pressure for temperature T [Pa]
p	=	air pressure [Pa]
T	=	temperature of the dry thermometer [°C] (dry-bulb temperature)
T_w	=	temperature of the wet bulb thermometer [°C] (wet-bulb temperature)

And for the saturation vapor pressure we can use the Magnus formulation:

$$e_s = 6.112 \exp\left(\frac{17.67 \cdot T}{T + 243.5}\right) \tag{4}$$

Equations (3) is derived from the heat balance equation: The evaporation heat is equal to the heat that is withdrawn from the air surrounding the thermometer.

The wet-bulb temperature T_w is the temperature an air parcel would have if cooled adiabatically to saturation at constant pressure by evaporation of water into it, with all latent heat being supplied by the parcel. The wet-bulb temperature is different from the dewpoint temperature, which is the temperature to which a given air parcel must be cooled at constant pressure and constant water vapor content in order for saturation to occur. Therefore, the wet-bulb temperature is always higher than the dewpoint temperature.

Evaporation increases with higher temperature. At the same relative humidity, the difference between wet-bulb temperature and dry-bulb temperature is larger with rising temperatures. Hence, the error for the measured humidity for the same difference between wet-bulb and dry-bulb temperature is larger at higher temperatures.

Evaporation over the sea is given by the following equation:

$$E = \rho\, C_D <u> (q_0 - q) \tag{5}$$

with

C_D	=	drag coefficient (in this experiment treated as constant)
ρ	=	air density [kg/m^3]
q	=	specific humidity [kg water/kg air]
q_0	=	specific humidity for saturated air over water at surface temperature T_0 (for calculation use equations (3) and (6) and replace T with T_0 [kg water/kg air]

The specific humidity q is defined as follows:

$$q = 0.622 \frac{e}{p} \qquad (6)$$

with p being the pressure of air [hPa].

2.3. Experimental tasks

2.3.1. Homogeneity of the wind profile

Test the homogeneity of the wind profile.

The wind velocity is to be recorded as a function of the motor speed. Use the wind velocities given in exercise 2.3.2.

Pay attention that nobody stands in front of the air intake during the measurement.

2.3.2. Evaporation

Depending on the wind velocity, the evaporated water volume is measured for a time span of 10 minutes as a function of the wind velocity. Select the wind velocities (2, 3, 4, 6, 7, 8, 10, 12, 14, 16) m/s for the experiment. Additionally, one measurement over 30 minutes is to be conducted in "stagnant air". For each measurement the dry-bulb and wet-bulb temperature are to be recorded.

Pay attention that no air bubbles are in the burette. May be that the filter might need to be changed. Refill the water reservoir for the wet-bulb thermometer if needed.

2.3.2.1. With airflow

Calculate the evaporation with equation (1). Verify the linear relationship between evaporation and wind speed (equation (2)). Any disagreements that may arise should be discussed. What is the value of α?

2.3.2.2. Without airflow

Comment on the situation with stagnant air (u=0).

2.3.2.3. Over the sea

Calculate a typical value for the evaporation over the sea [g cm^{-2} y^{-1}]. Be careful with the units! Use the following numbers in parentheses:

C_D = (10^{-3}), drag coefficient (10 m above sea level)
u = (4 m/s), wind speed
T-T_w = (3° C), difference between dry-bulb (air) and wet-bulb temperature
T_w = (13°C), wet-bulb temperature
T_0 = (19°C), sea surface temperature
p = (1000 mbar), air pressure

Compare the calculation with the result from the experiment (u=4m/s). Any disagreements that may arise should be discussed.

What do you obtain for the global yearly precipitation with the calculated evaporation?

2.3.3. Dependency of the psychrometer constant on the wind speed

Analyze the dependency of the psychrometer constant on the wind speed. Assume the water vapor pressure is constant during the time of the experiment. Evaluate the water vapor pressure by means of equation (3) by a wind speed of 2 m/s with the given psychrometer constant:

$\tilde{A}=6.6\cdot10^{-4}\,\mathrm{K}^{-1}$ psychrometer constant with an air stream velocity of 2 m/s

With the water vapor pressure as calculated by using equation (4) and the measured temperatures (T, T_w) the psychrometer constant for the other wind velocities can be determined.

3. Wind chill effect

3.1. Introduction

One of the principal modes of heat transfer from an object is convection to the surrounding air. Convective heat transfer increases significantly with increasing air velocity. Thus, a person is cooled at a faster rate under windy conditions than under calm conditions, given equal air temperature. Wind chill is a concept that relates the rate of heat loss from humans under windy conditions to an equivalent air temperature for calm conditions. The wind chill temperature (WCT) is an equivalent air temperature equal to the air temperature needed to produce the same cooling effect under calm conditions. Thus, it is not actually a temperature, but rather an index that helps relate the cooling effect of the wind to that of the air temperature under calm air conditions. It is important to remember that the wind will not cause an exposed object to become colder than the ambient air. Higher wind speeds will only cause the object to cool to the ambient temperature more quickly.

The Canadian and American meteorological offices use the following equation to determine the wind chill temperature:

$$T_{WC}=13.13+0.62\cdot T-(13.95-0.486\cdot T)\cdot v^{0.16} \qquad (7)$$

with

T = air temperature [°C]
v = wind speed 10m above ground [m/s]

The wind chill temperature is evaluated if the temperature falls below 8°C and the wind speed exceed 1.4m/s. Humidity and incoming radiation are not considered here.

3.2. Scientific basis

In our experiment a cylindrical block of copper simulates the human body. The heat flux through the surface of a body can be derived from the heat balance equation:

$$B+S+L+R=0 \qquad (8)$$

with

B = heat flux from the core to the surface
S = sensible heat flux from the air to the surface

L = latent heat flux to the surface
R = net radiation at the surface

In the case of a dry body the heat flux from the core to the surface equals the sensible heat flux plus net radiation.

The heat flux from the core to the surface can be expressed as follows:

$$B = -c \frac{m}{A} \frac{dT}{dt} \tag{9}$$

with

c = specific heat capacity of copper
m = mass of the body
A = surface of the body
$\frac{dT}{dt}$ = temperature change of the body

The sensible heat flux is proportional to the temperature difference of the body and the air:

$$S = -\alpha_L \cdot (T - T_L) \tag{10}$$

with

T = temperature of the body
T_L = air temperature
α_L = heat transfer coefficient [$Wm^{-2}K^{-1}$]

The heat transfer coefficient depends on the shape of the body and the ventilation. For a cylindrical body with airflow perpendicular to the axis we use the following approximation:

$$\alpha_L = 35 \cdot \sqrt{\frac{v}{d}} \tag{11}$$

with

v = wind speed [m/s]
d = cylinder diameter [cm]

For the net radiation we have:

$$R = R_s + R_l \tag{12}$$

with

R_l = long wave radiation
R_s = short wave radiation (sun)

In our case with the experiment in a closed room the short wave radiation is negligible. However, there is still an exchange of long wave radiation. With the assumption of black body radiation:

$$S_l = \sigma \cdot T^4 \tag{13}$$

with

σ = the Stefan-Bolzmann constant: 5.67e-8 W/m^2K^4
T = temperature of the body or environment

we can calculate the net long wave radiation (outgoing minus incoming long wave radiation).

3.3. Experiment

For the experiment the block of copper is to be heated up to both 40 and 60°C using a hot plate. After heating, the block is exposed to the wind in the wind tunnel. For the following ten minutes, the core temperature is recorded at one minute intervals. Calculate the instantaneous and the mean heat flux from the core to the surface according to equation (9). Repeat the experiment for wind velocities of 2, 6 and 10 m/s. Plot the calculated heat fluxes. Is there a difference between the measured heat flux and the heat flux derived from net radiation plus sensible heat flux? Comment on any disagreements.

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