The atmosphere of our Earth, of planets of our solar system and of exoplanets

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3. The Weather of our Planet
3.1 Weather: General
Weather is defined as the sensible, short-range state of the atmosphere, i.e. the observable state of the Troposphere at a particular location of the surface of the Earth. Important states are sunshine, cloudness, rain, wind, storms, hotness or coldness.

Meteorology classifies the spatial weather at a specific time on the basis of various phenomena in the Troposphere (Section 2.3).

In a strict physical sense, weather is a specific state at a well-defined location on the surface of the Earth. It specifies several properties such as gas pressure, gas density as well as the composition of the gas.

On the one hand, the primary driving force of weather is the energy radiation of the Sun, and on the other hand, it is the heat radiation from the Earth in the visible and infrared region back to the clouds and into free space.

The development of weather is, however, determined by the flow conditions in the atmosphere. The flow conditions depend on the air humidity and on the global wind systems. An other factor is the regional Albedo (strength of back radiation from the Earth’s surface), as well as other factors.

“April weather” is synonymous for fitful and rapidly changing weather in quick succession of sun, clouds and showers.
The color of sky at day

If the sunlight penetrates the atmosphere, part of the light is scattered and lights up the sky, producing the blue color. Without this scattering, i.e., without the atmosphere, the sky would be nearly black similar to the color of space. This diffuse radiation is due to a large part by the scattering of light by the oxygen and nitrogen molecules. Especially at twilight it is the absorption characteristic of Ozone in the Stratosphere which contributes to the color of sky.

During day, the blue color of the sky is due to scattering of the solar radiation by the molecules of Earth’s atmosphere. Visible light contains light with all wavelengths $\lambda$, ranging between about 400 nm (blue) and 700 nm (red) (s. Appendix 3-A-1-1). Thereby, light with short wavelengths is much more strongly scattered than red light with long wavelengths. It is the so-called Rayleigh-scattering which explains why during day the sky is blue. For the ratio of the cross section $\sigma$, which is a measure for the intensity of scattered light, one obtains for $\lambda_{\text{blue}} = 450$ nm , $\lambda_{\text{red}} = 650$ nm and with the corresponding refractive indices of air, $n_{\text{blue}} = 1.000275319$ and $n_{\text{red}} = 1.00027901$:

$$\frac{\sigma_{\text{blue}}}{\sigma_{\text{red}}} = (\frac{\lambda_{\text{red}}}{\lambda_{\text{blue}}})^4 \left(\frac{n_{\text{blue}} - 1}{n_{\text{red}} - 1}\right)^2 = 4.5$$

For the wavelengths $\lambda_{\text{blue}} = 390$ nm and $\lambda_{\text{red}} = 780$ nm we would even obtain a scattering ratio of about 16. Thus, blue light is much more strongly scattered than red light and for this reason the sky appears blue during a nice day.

The colors of sky at morning and evening

In the morning and in the evening the grazing incidence of the sun light through the atmosphere causes considerably longer path ways than during the day. For this reason, the blue light is much more strongly attenuated due to scattering by nitrogen-, oxygen- and water molecules than the red light. As a consequence, much more red light than blue light reaches the Earth’s ground during morning and evening. Both, the blue day-light (p. 61) as well as the dawn and red sunset of the cloudless sky can be explained by Rayleigh-scattering (colors of Sun-light: s. p. 3-A-1-1).

Red dawn sky before sunrise
Red sunset before sundown of the cloudless sky
3.2 Weather of the Troposphere

The humid Troposphere: Water vapor

The Figure illustrates a Section with the most important molecules in the Troposphere: Nitrogen (N₂: green), Oxygen (O₂: red) and Water molecules (H₂O: red – white). In contrast to other forms of water, water vapor is invisible. For typical atmospheric conditions, water vapor is continuously generated by evaporation of liquid water and continuously removed by condensation to liquid water. By these two processes, an equilibrium concentration is established which depends on the temperatures of the water sources (rivers, seas and oceans). [For information about water vapor see: P. Brüesch: p. R.0.B, Reference R.0.4, (WATER: pp 28 – 30)].
Absolute and relative Humidity, Saturation concentration

The Figure shows the absolute humidity $f_{\text{abs}}$ as a function of temperature. It is the mass $m_w$ of water vapor contained in a certain volume $V$, i.e. $f_{\text{abs}} = m_w / V$.

The maximum humidity $f_{\text{max}}$ is the maximum possible absolute humidity of air at a given temperature, i.e. $f_{\text{max}} = m_{w,\text{max}} / V$. It is reached if the partial pressure of water vapor in the air is equal to the saturation vapor pressure of water at the corresponding temperature.

The relative humidity is the ratio of the actual mass present in the air and the maximum possible mass. Or stated differently: it is the ratio of the absolute humidity of air and the maximum humidity of air at a given temperature: $f_{\text{rel}} = f_{\text{abs}} / f_{\text{max}}$.

The variations of water vapor in the air are very large, namely between 0 and 4 volume percent.

Example: at 50°C one obtains from the Figure or more precisely from a Table:

- $f_{\text{abs}}(50^\circ\text{C}) = 0.04135$ kg / m$^3$
- $f_{\text{max}}(50^\circ\text{C}) = 0.08278$ kg / m$^3$
- $f_{\text{rel}} = f_{\text{abs}} / f_{\text{max}} \approx 50\%$

Dew Point $(T_d)$ – Relative Humidity $(RH)$ – Temperature $(T)$ - 1

The dew point is the temperature to which humid air must be cooled down until it is completely saturated with water vapor. Hence, if the air is cooled down to the dew point, condensation of water begins.

If the air temperature $T$ is cooled down to $T_d$, condensation of water vapor to liquid water starts (dew, fog or clouds). The dew point $T_d$ is always smaller than or equal to the air temperature $T$: $T_d \leq T$.

The Figure to the left shows the temperature of the dew point $T_d$ as a function of the air temperature $T$ for different Relative Humidities RH: $T_d = f(T, RH)$.

For $RH > 50\%$ a simple approximate equation can be used:

- $T_d = T - (100 - RH) / 5$

Example 1: $RH = 60\%$, $T = 25^\circ\text{C}$

$T_d = 25 - (100 - 60) / 5 = 17^\circ\text{C}$

(s. point marked on blue line)

Example 2: $RH = 70\%$, $T = 35^\circ\text{C}$

$T_d = 35 - (100 - 70) / 5 = 29^\circ\text{C}$

(s. point on dark pink line)

For $RH < 50\%$ the relation for $T_d = f(T,RH)$ is more complicated (s. p 67).
A well-known equation for TP (in °C) as a function of RL (in %) and T (in °C) is the so-called August – Roche – Magnus Relation given below:

\[ T_d = \left( \frac{b \gamma(T, RH)}{a - \gamma(T, RH)} \right) \quad \text{with} \quad \gamma(T, RH) = \ln \left( \frac{RH}{100} \right) + \frac{a T}{b + T} \]

here \( a = 17.271 \) and \( b = 237.7 \) °C.

This relation is valid for \( 0 \text{ °C} < T < 60 \text{ °C} \), \( 1 \% < RH < 100 \% \) und \( 0 \text{ °C} < T_d < 50 \text{ °C} \).

Examples:

1. \( RH = 100 \% \) \( \Rightarrow \) \( T_d = T \);
2. \( RH = 30 \% \), \( T = 35 \text{ °C} \) \( \Rightarrow \) \( T_d = 14.81 \text{ °C} \);
3a) \( RH = 50 \% \), \( T = 10 \text{ °C} \) \( \Rightarrow \) \( T_d = 0 \text{ °C} \);
3b) \( RH = 50 \% \), \( T = 25 \text{ °C} \) \( \Rightarrow \) \( T_d = 13.84 \text{ °C} \);
4. \( RH = 70 \% \), \( T = 30 \text{ °C} \) \( \Rightarrow \) \( T_d = 23.9 \text{ °C} \).

A comparison with the values for \( T_d \) shows, that the results are in good agreement with the values of the Figure at p. 66.

For \( RH > 50 \% \) a very simple linear approximation for \( T_d = f(T, RH) \) with an accuracy of about 1% exists. This relation is:

\[ T_d \approx T - f \cdot (100 - RH) \quad \text{mit} \quad f \approx 0.2 \text{ °C} \]

Example: \( RH = 70 \% \), \( T = 30 \text{ °C} \) \( \Rightarrow \) \( T_d = 24 \text{ °C} \).
3.3 The World of Clouds

Formation of Clouds

Warm and humid air is lighter than its surrounding colder and dryer air and for this reason it rises to height. During this rise it cools down and hence the (molecular) vapor condenses into microscopic small droplets: a cloud is formed.
**Droplets and crystalites in clouds**

- **super-cooled small water droplet (cooled down as low as -12 °C)**
- **very small snow crystals**
- **Air containing water vapor and condensation nuclei (transparent!)**

**Nice weather cloud:** Accumulation of water droplets with diameters within the range between 1 to 15 μm (1 μm = 0.000001 m). Droplets are forming often at condensation nuclei (Aerosols). (Note that the droplets are pictured much too large!)

**Rain clouds:** Diameters of droplets as large as 2 mm → rain out!

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**Cumulus - Clouds**

Cumulus-cloud with anvil at the top (anvil cloud): contains very small water droplets and ice crystals.
Why do clouds not fall from the sky?

A water droplet in a cloud has a typical diameter of 10 μm and a small speed of fall of some cm/s (several 100 m/h).

But upwinds are counteracting the small speed of fall, causing the drops to float or even to move upwards.

Colours of clouds: white

This cloud is composed of very small and densely packed droplets such that the sunlight can not penetrate deeply before it is reflected. Since all colours are contained in the reflected light, its superposition combines to the observed characteristic white colour.
The sunlight is composed of several colours (red – green – yellow – blue,...), which combine to the white colour.

The colour of the cloud is the result of the scattering of the sunlight by the water droplets. Our eye observes the scattered (and reflected) light. The latter depends on different factors such as the size of the droplets, the viewing angle, the distance and the dust between the cloud and the observer.

If a large number of small droplets combine to large rain drops, then the distances between the drops become larger. As a consequence, light can penetrate much deeper into the cloud and is partly reflected and partly absorbed. Thus the reflection–absorption process gives rise to a whole range of cloud colors, which extends from grey to black.
Clouds at sunrise and sunset: dark-red - orange-pink

Such clouds can almost always be observed during sunrise or sunset. Their color is the result of scattering of sunlight by the atmosphere where the short-wavelength blue light is scattered most strongly. The clouds then reflect the remaining light which contains mainly the long-wavelength red light.

Structure and charge distribution of thunderstorm clouds

- Upper part: positive charge range, which can extend up to the anvil.
- Negative charge range in the lower part of the cloud.
- Small positive charge layer close to the base of the cloud which is generated by precipitations.

The detailed mechanism of the charge formation and of the charge separation is not clarified until now.
Threatening Thunderstorm Cloud
3.4 The Wind

The normal pressure of air is 1013 hPa (or 1031 mbar). Areas in which the air pressure is higher than this value are called High pressure areas, areas with lower pressures are Low pressure areas. Winds are pressure equilibrium currents flowing from high- to low pressure regions. This current persists until the pressure difference is equilibrated. Wind can therefore be considered as a mass flow, which according to the Second Law of Thermodynamics aspires an equipartition of particles in space towards a maximum entropy. The associated force is a pressure gradient. The stronger the differences between air pressures are, the stronger is the current of the air masses flowing from regions of high pressures towards regions of low pressures, and the stronger is the resulting wind.

The wind direction, most often in the direction of a principle wind direction, is determined by the locations of the high- and low pressure areas. However, this direction is deviated by the Coriolis force (pp 83–86): in the northern hemisphere it is deviated to the right, in the southern hemisphere to the left. Furthermore, below the free atmosphere, i.e. near the ground, the wind is also affected by frictional forces. In addition it can also be changed by morphological structures such as by mountains, valleys and canions (examples: foehn winds, fall winds, upcurrents (updrafts), valley winds, mountain winds). For rotating systems such as for cyclones (hurricanes), centrifugal forces play also an important role.

Beaufort scale for wind forces: In units of Beaufort (Bft) one is referring to brease (between 2 and 5 Bft), strong winds, near gale and stormy winds between 6 and 8 Bft. For wind forces of 9 Bft one is referring to a storm. For wind forces of 12 Bft we speak about hurricanes. The relation between the wind velocity v and the Beaufort force B (1 B = 1 Bft), is discussed in Appendix 3-A-4-1.
### Mountain and Valley Breeze

During the day, the air over the mountain slope heats up more than at the foot of the mountain. The warm air over the slope reduces in density. A low pressure (L) is created at the top of the mountain and a high pressure (H) from the cool air below, forces a cool breeze to move upward. This condition generates a breeze which we call Valley breeze (it starts at the Valley), and it is very common during warmer months when there is a lot of heating from the sun.

In the evening, it is a lot cooler as the sun goes to sleep. So the air at the upper slope of the mountain cools off very quickly and becomes dense. A high pressure (H) is created. At this time, the air at the valley floor is a lot warmer (low pressure L) and is forced to give way to colder air moving down the slope towards the valley floor. This is called mountain breeze (it starts from the mountain). And it is a lot common in the colder months where there is less warming from the sun.

### Land and Sea Breeze

As the names suggest, the two breezes occur along coastal areas or areas with adjacent large water bodies. Water and land have different heating abilities (heat capacities). Water takes more time to warm up and is able to retain the heat longer than land does.

In the day, when the sun is up, the land heats up very quickly and the air above it warms up a lot more than the air over the water. The warm air over the land is less dense and begins to rise. Low pressure (L) is created. The air pressure over the water is higher (H) with cold dense air, which moves to occupy the space created over the land. The cool air which comes along is called a Sea Breeze (it starts from the Sea).

In the night, the reverse happens. The land quickly loses its heat, while the water retains its warmth. This means the air over the water is warmer, less dense and begins to rise. Low pressure (L) is created over the water. Cold and dense air (H) over the land begins to move to water surface to replace the warmer rising air. The cool breeze from the land is called a Land Breeze (it starts from the land).
The direction of the wind gives it its name: North-east trade: north-east wind (H → L); South-east trade: south-east wind (H → L).

IZCZ: «International Convergence Zone» = zone near the equator in which there is very strong convection. The reason for this strong convection is the heating by the Sun.

The ITCZ is limited by the zones of the trade winds of the two Hemispheres. In the ITCZ there are substantial precipitations every day.

The strength of the Coriolis force depends on the rotational velocity and the latitude of the Earth. At the equator, the Coriolis force is zero and its strength increases by approaching the Poles. Furthermore, with increasing velocity the Coriolis force increases and as a consequence, the deviation of the wind direction increases with respect to the direction of the pressure gradient. If m is the mass of the air package moving with velocity \( v \) and if \( \omega \) is the angular velocity of the Earth-rotation, then the Coriolis force \( F_C \) is proportional to the mass \( m \) and to the vector product of \( v \) and \( \omega \) (s. p. 85).

Air under the influence of both the Pressure Gradient Force (PGF) and Coriolis force (CF) tend to move parallel to isobars in conditions where friction is low (1000 m above the surface of the Earth) and isobars are straight. Winds of this type are usually called geostrophic winds. Geostrophic winds come about because PGF and (CF) come into balance after the air begins to move. As the movement begins, th CF begins to influence the moving air causing it to deflect from the right of its path. This deflection continues until the PGF and CF are opposite and in balance with each other.
Wind current from High- to Low Pressures - Coriolis-Force

In the absence of Earth’s rotation the winds would simply follow the pressure gradient from the High-pressure areas H to the Low-pressure areas L. Because of the rotation of the Earth, this wind direction is deviated by the Coriolis force (pp 83, 84). The Coriolis force $\vec{F}_C$, which acts on an air package of mass $m$, is proportional to the mass $m$ and to the vector product of the velocity $\vec{v}$ of the air package and the angular velocity $\vec{\omega}$ of the system; in the present case it is the angular velocity of the Earth around the North–South axis:

$$\vec{F}_C = 2m(\vec{v} \times \vec{\omega}).$$

$\vec{v} \times \vec{\omega}$ is the vector product of $\vec{v}$ and $\vec{\omega}$, i.e. $\vec{F}_C$ is perpendicular to both $\vec{v}$ and $\vec{\omega}$.

The magnitude of $\vec{v} \times \vec{\omega}$ is equal to $v \cdot \omega \cdot \sin(\phi)$; $\phi$ = angle between $\vec{v}$ und $\vec{\omega}$.

Directions of air currents in High- (H) - and Low pressure (L) areas

Wind flows from High pressure area (H) to Low pressure area (L)

The numbers indicate the air pressure in hPa;

1 hPa = 100 Pa
1 Pa = 1 Pascal = 1 N/m²
1013.25 hPa = 1 atm

Isobars are lines with constant pressures

Since the wind directions at the northern and southern hemispheres are opposite (s. p. 83), also the directions of current are opposite.

Effect of Coriolis force on rivers

All motions on our Earth are subjected to the Coriolis force. As an example, the picture shows the undermining of a riverside by the Coriolis force acting on a river. At the northern hemisphere, the riverside to the right of the flow direction is underwashed, while at the southern hemisphere the riverside at the left of the flow direction is affected.

Two other examples: The motion of projectiles and trade winds (s. p. 83) are affected by the Coriolis force.
3.5 Precipitations and extreme Weather conditions

Shape of a Raindrop in a Wind channel

Only very small raindrops with diameters smaller than \( D = 140 \, \mu m = 0.14 \, mm \) are perfectly spherical. This is due to the high surface tension of water. Larger drops are, however, flattened.

If larger raindrops start to fall, their shape is also spherical but only at the beginning. After a short time their shape changes to a Hamburger-like bun: their ground base is flat but their upper face is rounded (s. Figure). This deformation is caused by their relative motion against the air.

This “pancake” shape of the drop is observed for individual drops of a uniformly falling rain. In a rain, drops with a whole distribution of drop diameters exist.

Fall velocities of raindrops:
- \( d = 0.5 \, mm \): 7 km / h; \( d = 1 \, mm \): 14 km / h
- \( d = 3 \, mm \): 29 km / h; \( d = 8 \, mm \): 43 km / h
The white arrows indicate the air stream around a large falling water drop. The raindrop is flattened on the bottom and with a curved dome top. Air flow on the bottom of the drop is greater than the airflow at the top. At the top, small air circulation disturbances create less air pressure. The surface tension at the top allows the raindrop to remain more spherical while the bottom gets more flattened out.

Shapes of vertically falling raindrops of different sizes

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Shapes of falling raindrops having different diameters (D in mm)

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Bergeron – Findeisen: Formation and Morphology of Snowflakes

Left-hand picture: Snow crystals develop, if water molecules of supercooled water droplets directly condense to ice which is followed by a subsequent growth of ice crystals.

Right-hand picture: The hexagonal symmetry of a snow crystal is ultimately due to the hexagonal symmetry of Ice Ih, which in turn develops from the hexagonal structure of H₂O – clusters (Ref. R.0.4. Chapter 2 - pp 41, 50). The shape of snowflakes depends on different factors, such as the temperature, the relative humidity and air currents. The „Water saturation“ – curve corresponds to the difference between the saturation vapor pressure of supercooled water droplets and snow crystals (Ref. R.0.4: Appendix 4-A-3-1).
The Fascination of Snowflakes

Snowflakes always have a hexagonal symmetry. This symmetry is already pre-formed in the hexagonal crystal structure. All snowflakes consist of a large number of small snow crystallites which stick together to form flakes during descending in air.

According to Bentley (1880), who collected and studied thousands of snowflakes during 40 winters, came to the conclusion that all of them had different detailed shapes!!

All snowflakes have hexagonal symmetry, but the detailed structure of all flakes are different!
Hail

**Formation:** Hailstones are formed in the inner layers of the thunderstorm cells where supercooled water transforms into ice with the help of crystallizing nuclei.

**The cycle of ice grains:** They are first lift upwards by the upwind, then they fall bag to lower air layers, take up more additional water, rise up again to higher levels whereby additional water is frozen at the surfaces.

This process is repeated several times up to the point where a hailstone is too heavy to be carried by the upwind.

**Fall velocity:** normally, the diameter $d$ of hailstones are about 0.6 to 3 cm. For $d = 3$ cm, the fall velocity is about 90 km/h.

Exceptions: diameters up to 10 cm with weights of more than 1 kg and fall velocities of more than 150 km/h have been observed!!

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**Hailstones after a Hailstorm**

After a hailstorm

Picture of one of the largest hailstones: diameter about 10 cm, weight about 154 g (from M. Schletter)

The hailstorm is compared with the size of a 9 Volt accumulator.

[The erinaceous structure is clearly observed which indicates the freezing of smaller grains to a larger one].
Cross section through a hailstone

The rings have been produced by the different depositions of layers during the complex vertical growth of the hailstone.

Lightnings and Thunder - Zeus has struck a terrible blow!!

In nature, a lightning is a spark discharge or a short-time arc of light between clouds or between clouds and Earth. As a rule, a lightning occurs during a thunderstorm due to an electrical charge of the water droplets or raindrops. The lightning is accompanied by thunder and it belongs to the so-called electrometeors. During this process, electrical charges (electrons and gas-ions) are exchanged and strong electrical currents are flowing. Depending on polarity, discharges can occur also from ground to clouds (upward lightnings).

A more detailed discussion of the formation, properties and dangers of lightnings is given in Chapter 8, Section 8.1, pp 335 – 348.

- electrical voltage: some 100 million Volts!
- electrical currents: several 100’000 Ampère!
- maximum air temperature: up to 30’000 °C!
- local air pressure: up to 100 atmospheres!
- explosion of air: thunder!
Tornadoes

Tornadoes are packed into tight, swirling spirals of power. The winds of the most powerful tornadoes can reach speeds of approaching 515 km/h; they are the most violent winds on Earth. They are faster than many airplanes can fly, and almost half the speed of sound. The vast majority of tornadoes, however, range at less than 322 km/h.

Tornadoes are quite small as atmospheric phenomena go. The width of the funnel at ground-point usually ranges from a few dozen to several hundred meters at ground-point. Yet, because tornadoes move rapidly along the ground, they can cause damage over a larger area than their small size might suggest.

Tornadoes tend to occur over flat terrain, but can travel across mountains and form over water. Tornadoes are most common and most powerful in the United States. When Tornadoes strike near populated areas, the damage can be severe. Due to their size and behavior, most damage is localized and random.

Tornadoes are powerful killers; in the US, an average of 100 people is killed each year. Tornadoes pack the most destructive force of any atmospheric phenomenon, possessing a violence unmatched by any other force of nature.

Hurricane Isaac

- **Formation at:** 21. August 2012
- **Ending at:** 1. September 2012
- **Top speed:** 130 km/h; (during 1 Minute)
- **Deepest air pressure:** 968 mbar
- **Victims:** 41 (direct), 3 (indirect)
- **Damages:** 2 Billions US $
- **Affected areas:** Cuba, Jamaica, Bahamas, Florida, Alabama, Mississippi, Louisiana, Texas …

A Hurricane is defined as a tropical cyclone if it reaches at least hurricane strength. This means that its wind strength is at least 12 in the Beaufort scale. This corresponds to more than 118 km/h. A Hurricane develops over warm tropical areas. As a rule, Hurricanes arise between May and December, most of it between July and September.

The word «Hurricane» originates from the notion «Huracan». In the language of the Taino- and Maya-languages this means the «God of Winds».
Hurricane Sandy - 2012

Wind path of Hurricane
(bottom up)

- Canada
- East coast USA
- Bahamas
- Cuba
- Jamaica
- Dominican Republic
- Haiti

- Formation at: 19. October 2012
- Ending at: 29. October 2012
- Top speed: 185 km/h
- Lowest air pressure: 940 mbar (hPa)
- Victims: 209 (direct)
- Damages: 52.4 Billion US $
If we speak about wind energy, it is the kinetic energy of the moving air masses of the atmosphere. Since this energy is replaced relative quickly through the influence of the Sun, this energy is referred to as a renewable energy.

The wind energy utilisation by using windmills (today for the production of electrical current with the aid of wind energy stations), has been used since the antiquity for the production of energy from the environment. The windmill is an antic technical structure, which produces energy by setting in motion the wings of the windmill.

Historically, windmills and watermills were the only pre-industrial power machines of humanity. They have been used for a variety of applications such as for grinding mills, oil mills (for the production of plant oil from oil seats), for processing of raw materials (by means of sawmills, for example), as well as for pump stations and sewage pumping stations.

In addition to the production of mechanical power, today, the electrical power is of great importance. The kinetic energy is $E_{\text{kin}} = \frac{1}{2} \, \text{dm} \, u^2$ where $u = \text{ds}/\text{dt}$. The power is $P = \frac{dE_{\text{kin}}}{dt} = \frac{1}{2} \, (\frac{\text{dm}}{\text{ds}}) \, (\frac{\text{ds}}{\text{dt}}) \, u^2 = \frac{1}{2} \, (\frac{\text{dm}}{\text{ds}}) \, u^3$. If $dV = A \, ds$ is the volume element of the wind package, $\rho$ its density and $\text{dm}$ its mass, it follows $\text{dm} = \rho \, dV = \rho \, A \, ds$ and $\text{dm}/\text{ds} = \rho \, A$. Replacing $\text{dm}/\text{ds}$ in the expression for $P$ and adopting an efficiency factor $k < 1$, we obtain:

$$P = k^{*} \, (1/2)^{*} \rho^{*} A^{*} u^3.$$ 

Thus, the power is proportional to the cube of the wind velocity $u$. A realistic value for the efficiency factor is $k \approx 0.4$. 

$$\frac{101}{3 - 24}$$
The Britzer Windmill has been constructed at 1865 in the Britz Garden in Berlin. The 20 meter, twelve-cornered Dutch-type windmill rises high in the air with its 12 meter wings at the centre of an expansive orchard at the edge of the Britz Gardens.

A windrose automatically turns the cap mounted on cast-iron rollers. The Britz Windmill (Britzer Mühle) is equipped with two stone millstones and operated until 1936: after that it converted to the use of a Diesel engine.

Achievable electric Power $P$ is proportional to the third power of the wind velocity $u$: $P \sim u^3$ (s. p. 101). Based on conservative assumptions, scientists from Harvard University evaluated at 2009 the global potential of wind energy. They came to the conclusion that the global wind energy surpasses the electrical energy demand by a factor 40, while the total wind energy is 5 times larger than the overall needed energy.

Because of the irregular nature of wind current, the generated electrical energy must be combined with other energy sources in order to achieve a continuous energy supply. An other possibility is storage via wind gas. (From the electrical current produced by wind energy, natural gas ($\sim$ CH₄O) can be produced).

Transmission of high voltage DC (Direct Current) as produced by Wind farms over large distances is not easy because of transmission losses and electrical breakdown, but laboratory experiments of ABB and other Companies are promising.
The installed power is the maximum power of a Wind farm, in our case the maximum power of all built wind power plants. In other words, we are referring to the so-called rated power. This is the maximum possible power and not the actually produced power.

\[1 \text{ GW} = 1 \text{ Gigawatt} = 1000 \text{ millions Watt} = 10^9 \text{ Watt}\]

Other
- Denmark
- India
- Spain
- China
- USA
- Germany

A wind tunnel is used to study and measuring the aerodynamic and aeroacoustic properties of objects. Very well known examples are the wind tunnel study of cars and of aeroplanes (s. Chapter 4). Concerning cars, it is important to achieve a low air resistance and an optimal lift coefficient. For airplanes (Chapter 4), considerably more aspects play a role: in addition to to air resistance and lift, other important factors are airfoil, stability and control, etc.

Today, other objects are railways and ships which are evaluated extensively in wind tunnels. Of importance are also aerodynamic properties buildings, especially high-rise buildings, of chimneys and of bridges.

1) Rectifier: avoids air turbulences and ensures a uniform distribution of air in the wind tunnel.
2) Assures a uniform velocity profile in the wind tunnel
3) The arrow marks the flow direction
4) Section for measuring the model object
5) Diffuser: for pressure regain
6) Blower: for suction of air, thereby creating the air current

The open design of the wind tunnel is also known as the Eiffel wind channel in memory of the man who constructed the Eiffel-Tower. In this design, the air is sucked off from the environment, flows through the air channel and finally escapes out of the tunnel. Advantages of this design are: Cost-effective, easy to implement and moderately susceptible with respect to self-contamination such as by smoke. Disadvantage: Dependence on the sucked air which can cause temperature- and pressure fluctuations.
Dispersion of Sunlight

In connection with the colours of the sky at day and at night (pp 61, 62), we consider the spectral decomposition of white light emitted by the Sun into its spectral colours.

Due to the non-normal incidence of light and due to the refractive index \( n = n(\lambda) \) (\( \lambda \) = wavelengths of sunlight) of the prism, the incident light beam is refracted by the prism at different angles. This effect is reinforced at the exit surface of the prism, where the refracted light beam leaves the prism at widely different exit angles. [For quartz (SiO\(_2\)), \( n(400 \text{ nm}) = 1.55773 \) and \( n(650 \text{ nm}) = 1.54205 \). Visible range (VIS): 380 nm < \( \lambda < \) 780 nm; (1 nm = 10\(^{-9}\)).
Mie scattering dominates at days where large particles are in the air – examples are water droplets in clouds, dust or smoke. These particles are considerably larger than the wavelengths of visible Sunlight with which they interact. ( wavelength $\lambda$ of green light is $\approx 500$ nm $= 0.5$ $\mu$m (s. p. 3-A-1); diameters of water droplets for nice weather clouds range between $\approx 1 – 15$ $\mu$m (s. p. 70)).

If such radiation interacts with particles of this size, there is no preferential scattering of particular wavelengths. All wavelengths are uniformly scattered and for this reason, the scattered light remains white (s. p. 70). For large particles (water droplets of nice weather clouds), the incoming sunlight is strongly forward scattered (right-hand Figure).

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**Stratospheric Clouds**

Polar Stratospheric Clouds (PSC’s) are present in the Stratosphere in altitudes above 20 km, often between 22 km and 29 km. The formation of PSC’s is possible if the temperature is lower than -78 $^\circ$C. This happens regularly in the polar regions beyond 80$^\circ$ of northern and southern latitudes, respectively. On the southern hemisphere, PSC’s are considerably more frequent.

In the stratosphere, the concentration of water vapor is very low, and therefore water clouds as in the Troposphere do not exist. PSC’s consist of crystallites of sulfuric acid ($H_2SO_4$) or of nitric acid (HNO$_3$). If the temperatures are very low, the acidic crystallites can be covered by a thin layer of water ice. On the surface of the crystallites, chemical reactions can take place. These reactions are of importance for ozone depletion.

The defraction and interference of sunlight by these ice crystallites often produces pearly colors. It is for this reason that PSC’s are also referred to as «mother-of-pearl clouds». This coloration is most clearly visible if the Sun is already one to six degrees below the horizon.
The Beaufort - Scale

The Beaufort scale is a scale for the classification of winds according to their velocity. It is the most widespread system for the description of wind velocities. The scale is named after Sir Beaufort (in units of Bft), although his contribution to its development is rather modest. After a Revision at the year 1946, the following relation between the wind velocity \( u \) and the wind strength in Bft has been adopted:

\[
u = 0.8360 \text{ m/s} \times \text{Bft}^{3/2} \quad \text{or solved for Bft} : \quad \text{Bft} = \left( \frac{u}{0.8360} \right)^{2/3},
\]

Here, \( u \) is the wind velocity at 10 m above the surface. If \( u \) is expressed in units of km/h, the relation is: \( u = 3.010 \text{ km/h} \times \text{Bft}^{3/2} \). (The Beaufort scale varies between 0 and 12: 0 ≤ Bft < 12).

Dynamics of falling Hailstones and Raindrops

Let \( v(t) \) be the velocity of the particle in the air (Graupel, Hailstone or water drop) at time \( t \). At \( t = 0 \) we assume that the velocity of the particle is zero: \( v(0) = 0 \). The total force acting on the particle of mass \( M \) has three contributions: the weight \( G \), the friction force \( R \) and the buoyant force \( L \); \( K = G - R - L \). Since the densities of hailstones or raindrops are much larger than the density of air, \( L \) can be neglected i.e.

\[
K = G - R
\]

(1)

The weight is \( M \) \( g \) \((g = 9.81 \text{ m/s}^2 = \text{gravitational acceleration})\). For larger particles one has to use the Newton friction force which is proportional to the \( v^2 \) [for falling dust particles, \( R \) is proportional to \( v \) (s. Chapter 5, pp 221 – 231)]. In the present case, Newton’s friction force is

\[
R = \left( \frac{1}{2} \right) \rho_A C_w A_H v^2
\]

(2)

Here, \( \rho_A \) is the density of air, \( A_H \) is the cross section of the particle and \( C_w \) is the so-called drag coefficient. To calculate \( v(t) \) of a Hailstone \( H \) with mass \( M_H \) and density \( \rho_H \), the following differential equation must be solved:

\[
K_H = M_H \frac{dv}{dt} = - M_H g - \left( \frac{1}{2} \right) \rho_A C_w A_H v^2
\]

(3)

The solution of this equation with the initial condition \( v(t = 0) = 0 \) (s. Ref. 3.A.5.1) is

\[
v(t) = v_{\text{term}} \times \tanh \left( \frac{g t}{v_{\text{term}}} \right)
\]

(4)

where \( \tanh \) (\( x \)) is the hyperbolic tangent function of \( x \). \( v_{\text{term}} \) is the constant rate of descent after a sufficiently long time:

\[
v_{\text{term}} = \sqrt{2 M_H g \left( \frac{\rho_A A_H C_w}{3} \right)}
\]

(5)
The Figure below illustrates the fall velocities $v(t) = v_{\text{term}} \tanh [(g \cdot t / v_{\text{term}})]$ (eq. 4). Let $\rho_H$ be the density of the Hailstone and $V_H = (4\pi/3) R_H^3 = (\pi/6) D_H^3$ its volume; then we have $M_H = \rho_H V_H = (\pi/6) D_H^3 \rho_H$ and $v_{\text{term}} = 2 [(D_H g / 3 C_w) (\rho_H / \rho_A)]^{1/2}$ (eq. 5). Density of Hail: $\rho_H \approx 0.8 \text{ g/cm}^3 = 800 \text{ kg/m}^3$; density of air: $\rho_A \approx 1.2 \text{ kg/m}^3$; drag coefficient $C_w \approx 0.5$. The curves have been constructed by P. Brüesch with the help of the Maple 13 Program. The black dashed line $v = g \cdot t$ is the tangent to the curves passing through the origin of the coordinate system and describes the free fall of the masses in vacuo.

Terminal velocity of fall of a Hailstone as a function of diameter

In the following we discuss the terminal velocity of fall, $v_{\text{term}}$, as a function of the particle diameter $D_H$ of the Hailstone. For a spherical Hailstone, the mass $M_H$ appearing in eq. (5) of p. 3-A-5-1 is given by $M_H = (\pi/6) D_H^3 \rho_H$ and its cross section is $A_H = (\pi/4) D_H^2$. Substitution into eq. (5) gives:

$$v_{\text{term}} = 2 \sqrt{(D_H g / 3 C_w)(\rho_H / \rho_A)}$$

(6)

The diagram below has been calculated with a drag coefficient $C_w = 0.5$ which corresponds to a large Reynolds number (s. p. 3-A-5-3, d).

Parameters for calculating $v_{\text{term}}(D_H)$:
- $g = 9.81 \text{ m/s}^2$
- $C_w = 0.5$
- $\rho_H = 800 \text{ kg/m}^3$
- $\rho_A = 1.2 \text{ kg/m}^3$

For the terminal fall velocity $v_{\text{term}}(D_H)$ shown in the Graph, the values of the forces $G_H$ and $R_H$ are equal and hence, the resulting force is zero.
For describing the distribution of Hailstones we adopt the so-called two-parametric Gamma-distribution. This distribution is defined as follows:

\[ y_{a, \beta}(x) = \frac{\beta^a}{\Gamma(a)} x^{a-1} \exp(- \beta x) \]  

(1)

Here, \( \alpha \) and \( \beta \) are two positive parameters; \( \Gamma(a) \) is the Gamma function of \( \alpha \) and \( \exp(- \beta x) \) is the exponential function of the variable \( x \).

For the distribution of the diameters \( D_H \) of Hailstones we use an equation analogous to eq. (1) but with different notations:

\[ f(D_H/D_0) = N(D_H)/N_0 = \left[ \lambda^a / \Gamma(a) \right] (D_H/D_0)^{(a-1)} \exp[- \lambda (D_H/D_0)] \]  

(2)

\( N(D_0) \) is the number of Hailstones with diameter \( D_0 \) per m\(^3\), \( N_0 \) is the total number of Hailstones per m\(^3\), and \( D_0 = 1 \) cm is the unit diameter. In eq. (2), \( n \) corresponds to \( \alpha \), \( \lambda \) to \( \beta \) and \( D_H/D_0 \) to \( x \) of eq. (1). By equating the first derivative of \( f(D_H/D_0) \) with respect to the variable \( D_H/D_0 \) equal to zero (maximum of \( f(D_H/D_0) \)), one obtains \( \lambda (D_H/D_0) = n - 1 \), where \( D_m \) is the diameter of the maximum of \( f(D_H/D_0) \). For simplification we put \( n = 3 \) and using \( \Gamma(3) = 2 \) we obtain:

\[ f(D_H/D_0) = N(D_H)/N_0 = \left[ \lambda^3 / 2 \right] (D_H/D_0)^2 \exp[- \lambda (D_H/D_0)] \]  

(3)

Some examples (compare with the Figure of p. 3-A-5-5):

\[ D_m = D_0 \rightarrow \lambda = 2; \quad f(1) = 0.541; \quad D_m = 2 D_0 \rightarrow \lambda = 1; \quad f(2) = 0.270; \quad D_m = 3 D_0 \rightarrow \lambda = 2/3; \quad f(3) = 0.180; \quad D_m = 5 D_0 \rightarrow \lambda = 0.4; \quad f(5) = 0.108; \quad D_m = 6 D_0 \rightarrow \lambda = 0.3333; \quad f(6) = 0.090. \]

Normalized number of Hailstones \( f(D_H) = N(D_H)/N_0 \) as a function of diameter \( D_H \). \( N_0 \) is the total number of Hailstones per m\(^3\). The curves have been calculated for 6 mean diameters \( D_m = 1, 2, 3, 4, 5, \) and \( 6 \) cm on the basis of two-parametric Gamma-distributions (s. p. 3-A-5-4). Inset: at the origin \( D_H = 0 \), the curves have zero slope. Graupel, also called soft hail, are not shown in the Inset; they have diameters ranging between 0.2 und 0.5 cm and are composed of snow pellets encapsulated by ice.
References: Chapter 3

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Library of Congress Cataloging-in-Publication Data
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b) Morgenröte - http://de.wikipedia.org/wiki/Morgen%C3%B6te
Left-hand picture: Sunrise. from www.google.ch/search - Images
Right-hand picture: Sunset. from www.google.ch/search - Bilder

3.2 The humid Troposphere

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R-3-3
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### R.3.3.4 p. 72: Why do Clouds not fall from the Sky?

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### R.3.3.7 p. 75: Colours of Clouds: white-gray – dark-gray - Regenwolken: foto community.de

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c) Passat (Windsysteme) - http://de.wikipedia.org/wiki/Passat_(Windsystem)

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   Left-hand Figure: Coriolis acceleration as a function of latitude:
   Right-hand Figure: Air under the influence of both the pressure gradient forces and the Coriolis Force
   Note: Force = mass m x acceleration a: Coriolis Force: \( F_C = m \times a_C \)
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Source: Falling raindrop in the wind channel: jpg: Film und Standard
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b) left-hand picture: from «Der Bergeron-Findeisen-Prozess-ethz.ch»
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a) Fotos found under - »Snowflakes« - Bilder → Schneeflocken w0401226077.jpg
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### 3.6 Wind energy

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<td>a) Reference R.3.6.1 // Graph of globally installed windpower from: <a href="http://www.volk-wasschling.de/darwin/windinst/index.htm">www.volk-wasschling.de/darwin/windinst/index.htm</a></td>
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<td>b) (The names of the Countries have been changed from German to English by P. Brüesch)</td>
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3.A.5.2 Velocities v(D,t) of falling Hailstones
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3.A.5.3 Terminal fall velocities of Hailstones

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3.A.5.4 Size distribution of Hailstones - Mathematics

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