Dew

Auteur :
BEYSENS Daniel, Président de l'OPUR (Organisation Pour l'Utilisation de la Rosée) et Directeur de Recherches Honoraire du laboratoire PMMH (Physique et Mécanique des Milieux Hétérogènes) de l'ESPCI–PSL (Ecole Supérieure de Physique et Chimie Industrielle – Paris Sciences & Lettres).

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Everybody knows or has experienced what is dew, when soil and plants are wet in the morning of clear and calm nights or when water flows on the walls and windows of kitchen and bathrooms. But where dew comes from? Its origin has long been a mystery. From alchemist to scientists many savants have elaborated more or less rigorous theories. It is only in the middle of the XXth century that a comprehensive interpretation of dew was elaborated. Dew is beneficial to plants and animals, but can it be used by humans as a new source of water? How to harvest dew? What are the chemical and biological qualities of dew? Is it potable? All these questions are answered in this article.

1. Dew: a long history in mysteries

Everybody knows what dew is. But **where dew comes from?**

Natural dew is a ubiquitous phenomenon, already noted in the oldest literature. For instance, in the Hebraic bible (*Ecclesiaste* 1:2) the famous words “All is vanity” correspond actually, in Hebrew, to the word dew, highlighting dew beauty and brightness but also dew ephemeral nature. In Japanese culture, many Haikus have been written with dew. These are some of the many examples of dew as used in art and literature.

In contrast to natural dew, which essentially forms outside, there is **another dew** which is found on the cold walls of caves and humid rooms such as kitchens, bathrooms and laundry rooms. The difference comes from the **origin of cooling**: natural dew originates from a radiative exchange with the cold sky and is efficient only outside while the other “dew” proceeds from contact cooling. It is the same "dew" as the "breath figures" that form on a glass when you breathe on it.

People have indeed been long fascinated by dew. They could not understand how water could cover the ground and plants at night even though the sky was clear. A major step has been reached with Leroy (1751) [1] who understood that water can be dissolved in air like sugar in water, with the highest the temperature, the largest the dissolution. Then cooling warm humid air leads inevitably to extract liquid water, precisely at the dew point temperature. Wells (1866) [2]carried out the first comprehensive study of dew condensation but did not explain the reason of nightly cooling. The latter process has been highlighted by Jamin (1879) [3] with **radiative cooling**. It is only much later that Monteith (1957) [4] formalized dew formation by using a full energy balance.

1.1. Dew, a new source of water?

Figure 1. Dew water collection by alchemists [Source : adapted from Mutus Liber, 1677 [1]].

Dew water has long been neglected as a supplementary source of water. It can, however, be a **source of fresh and pure water for plants, animals and humans**. Dew water is indeed drunk by many small animals and insects, especially in arid and semi-arid regions (but not only, there are many examples of animals, like cats and dogs, drinking in our countries dew water). The survival of horses in Namibia when abandoned after First World War is said to be due to the fact they could leap dew on the train tracks.

Figure 1. Dew water collection by alchemists [Source : adapted from Mutus Liber, 1677 [1]].

The first documented human use of dew water is perhaps dew collection by alchemists, noted in the book Mutus Liber(1677) [5] , called the "Mute Book" because it is composed only of drawings. In Figure 1 dew is collected at night (noted by the moon) on horizontal sheets stretched over sticks. Water is then recovered by squeezing the sheets on a basin. The next documented attempts are concerned with massive dew **condensers**, working on temperature inertia, and then corresponding to non-radiative dew type. Such condensers are described below in Section 2.3.

Radiative condensers have been the object of several studies since the trials of massive condensers. Many areas of science and technology are indeed concerned in the process of dew **condensation and collection**, allowing many ideas for improvement to be tried: atmospheric optics and physics, radiative, conductive and convective heat exchanges, hydrodynamics, chemistry, biology. Simple large planar condensers have been erected (Figure 2a), more sophisticated dew plants, made of ridges (Figure 2b), have been constructed . Many other kind of radiative dew condensers (conical-like, origami, etc.) were designed to increase cooling and dew drop collection. They are presented in the book Dew Water (2018) [6].

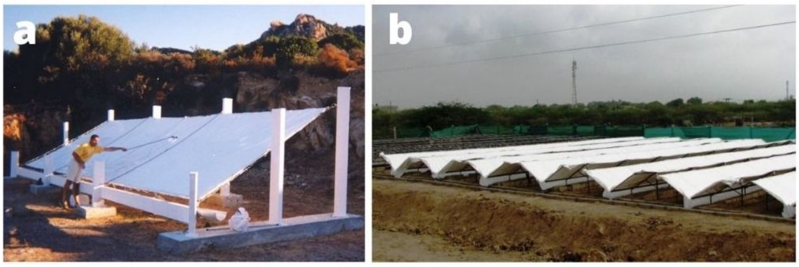

Figure 2. Some large radiative dew condensers. (a) In Ajaccio (Corsica island, France). [Source : Photo D. Beysens]. (b) In Kothara (N-W India) [Source : Photo G. Sharan].

The interest of such radiative condensers is their **simplicity, cost effectiveness, robustness** (they can still work even partially damaged), and the fact that **no energy is needed**. The process is sustainable, clean, and gives good quality water. The yield is however limited to the available energy, on order of 60 W.m^{-2}, which limits the water yield to near 1 L.m^{-2}. However, the actual yield is often much larger as the technologies which are used allow the weak precipitations, usually lost, to be recovered.

1.2. Dew on plants

Dew condensing on plants can bring moisture and helps to fight again drought periods. Plants can absorb water through their leaves to compensate for depleted water tables and survive drought. More complex scenarii can, however, **help plants**. For instance, the biological soil crust (Read : Lichens, surprising pioneering organisms) can retain and use water from dew to increase the concentration of dissolved organic nitrogen, associated with the fixation of atmospheric N_2 by cyanobacteria and cyanolichens. Dew can also prolong seedlings life under drought stress conditions.

On the other hand, dew, in addition to high relative humidity, can influence the occurrence of plant disease with moisture on plant surfaces promoting the **development of pathogenic** germs and increasing disease frequency in many crops. Cryptogrammic diseases are observed on grass, banana and potatoes leaves. However, the development of such fungi can be sometimes beneficial. This is the case for the elaboration of some sweet wine. For instance, the famous Sauternes vineyard "noble rot" is known to come from the action of *Botrytis Cinerea* fungus.

2. How to collect dew?

2.1. Dew yield

According to the preceding Sections, the collecting surface has to **reach the dew point to initiate condensation**. The surface will be thus below the air temperature and heat losses, triggered by wind, will be present. An energy balance can be written where, in the steady state, the radiative cooling power R (in W. m^{-2}) (see Focus 1) counterbalances heating by air losses, proportional to the difference between air temperature and dew point temperature , and heating by the release of latent heat L (Read : Pressure, temperature and heat), such as $R + a(T_a - T_d) + L(dm/dt)/S = 0.$

Here S (in m^2) is the condensing surface and a (in W.m^{-2}.K^{-1}) is the heat transfer coefficient [7], which increases with wind speed. Condensed mass is m (kg), related to condensed volume V (m^3) by the water volumic mass (kg.m^3) through . Time is denoted by t (in s). The quantity L is the latent heat (in J.kg^{-1}). One can readily deduce the condensed water volume per surface area, classically expressed in litres per square meter, or mm. For the ideal case where the atmosphere has a large relative humidity, giving , the maximum yield, only limited by the available power (see Figure 1 of Focus 1 for its value according to air temperature and humidity) is on the order of 1 mm per night.

2.2. Radiative dew collectors

The oldest mentioned dew condenser to our knowledge is reported in the "Dumb book" for Alchemists (Mutus liber, 1677 [5]) where horizontal cloths are fixed to sticks and then soared by hand (Figure 1). In dew collectors one has to consider **two processes, dew condensation and drop collection**. Both processes are of importance. According to the previous Section, the dew yield increases with radiative power and decreases with wind speed. In Focus 1 details on radiative cooling are given. It is shown that the **cooling power is proportional to the condensing surface emissivity (or absorptivity) –** the ability of a material to emit and absorb light – and to the difference of the atmosphere emissivity with 1. It thus comes out that, under given conditions of atmosphere emissivity and wind speed, the **dew yield can be improved** by (i) lowering atmosphere emissivity, (ii) increasing condensing surface emissivity, (iii) decreasing heat exchange with surrounding air and (iv) increasing the efficiency of the dew drop collection.

One can **lower the atmosphere emissivity** (point (i)) by considering a condenser design that uses only the near zenith angle of the atmosphere, where atmosphere emissivity is the lowest (see Figure 2 of Focus 1). Surface emissivity (point (ii)), if not too low, is that of water and cannot be changed. However, having a substrate of low emissivity and thus **absorptivity** only for the solar radiation spectrum permit better cooling of the condenser at the end of the day and in the morning, making longer the duration of dew condensation.

Figure 3. Various dew collectors: a : Plane; b : Cone [Source : Photo O.Clus] ; c: Origami and "egg-box" [Source : Photo D.Beysens].

Point (iii) about heat losses can be met by using hollow shapes that lower the wind influence. Good thermal isolation has also to be made below the condensing surface to lower the heat losses with air. **Heat losses can be reduced by using symmetrical or near symmetrical hollow structures** (ridges, origamis, egg-box, inverted pyramids, hollow cones, see Figure 3). Ridges act as hollow forms except when the wind is aligned with the rows (Sharan et al., 2017 [8], see Figure 2b). However, simple planar forms as encountered with roofs, can give good results if properly designed (see Figures 3 & 4).

Concerning drop collection, point (iv), passively **harvesting by gravity** the weak dew events without scraping is indeed a major challenge. There is a basic contradiction between having a surface facing the zenith and also having the maximum surface tilt angle for easy drop sliding by gravity. It has been shown [9] that a surface tilt angle in the **range 20° – 30°** gives the best results.

Figure 4. Drops sliding on the corrugation galvanized iron roof in Combarbala (Chile) with small tilt angle (»15°). P: Painted part with additives (OPUR [12]) where dew forms and drop slide down on the corrugations (arrows). NP: Non painted part where dew does not form. [Source : J.-G. Minonzio].

Many materials have been tried for collecting drops by gravity. A first solution is to increase the natural wiping effect of drops from boundaries which, sliding earlier, sweep the other drops. Dew yield increase up to 400 % has been observed with origami shapes [10]. Increasing the length of edges has, however, a limit since it can also enhance the heat exchange. Another solution is to locally increase the angle with horizontal as it is e.g. performed with corrugated steel roof (Figure 4). **Wetting surface properties** are also important. For example, additives give better sliding properties (and emissivity) to paints as shown in Figure 4. Increased roughness by sand blasting also gives good results because the number of nucleation sites [11] is increased. **Microgrooved surfaces** are seen to considerably improve drop collection There is a huge amount of literature on the subject because improving drop sliding also increases the yield of thermal exchangers by a large factor. However, although several solutions exist in the laboratory to improve dew collection, as e.g. the "Lotus" effect where drops pinning on the surface is very weak (Read: Between protection and defence: the plant cuticle), making them to roll down easily, the main **challenge remains materials aging.** Keeping good sliding properties under many cycles of functioning, especially under outdoor conditions, is quite difficult to maintain. Paints with additives have shown to last on at least 10 years. Low density polyethylene foils with anti-UV additive can last 3-4 years. Sand blasting and presumably grooves, although not yet systematically tested outdoor, looks a good solution to last long.

2.3. Massive dew collectors

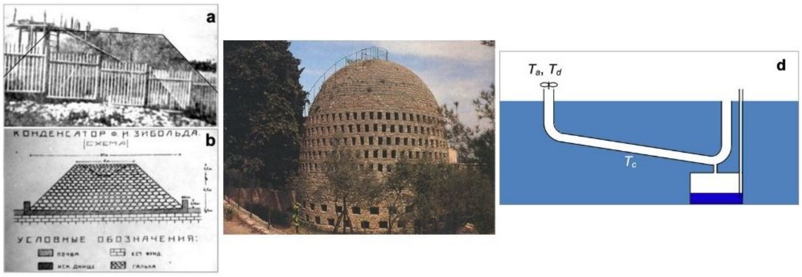

Figure 5. Massive condensers. (a-b) Zibold condenser. (a) Photo with the platform for instrumentation (adapted from Tougarinov, 1935 [15]. The condenser is highlighted by black lines.(b) Schematics. [Source : Adapted from Totchilov, 1938 [16]]. (c) Knapen condenser in Trans-en-Provence (France), still visible (2017) [Source : Photo D. Beysens]. (d) Schematic design of an underground massive condenser where air is blown only if Ta, the air temperature < Tc, the underground temperature or Tc <Td, the air dew point temperature .

Massive condensers work on temperature inertia, cooled below the dew point temperature during the coldest period of the year. The Russian engineer Zibold believed – erroneously, see Nikolayev et al. (1996) [13] – that dew water was an important source of water used by ancient Greeks to feed the 101 fountains in Feodosia (Crimea, Ukraine). Zibold, however, confused the many piles of stones on the hill above the city with dew condensers and constructed in 1914 (Figures 5ab; Mylymuk-Melnytchouk and Beysens, 2016 [14]) a massive dew condenser based on these piles of stones: a truncated cone made of sea pebbles with a hollow at the top. The very low water yield was supposed to be due to fissuring of the condenser base. The project stopped definitively with the Bolshevik revolution in 1917. Archeological excavations on the Mont Tepe-Oba above Feodosia proved later that these piles of rocks were Scythes or Greek tombs, protected by rocks (Nikolayev et al. 1996 [12]) from grave robbers. The through at the top was the traces of the unfruitful efforts of the robbers.

Soviet scientists [14], just like their counterparts in France, Knapen [17], and Chaptal [18], which had heard of the Zibold condenser, got interested again in the collection of water of dew by this technique of massive condensers. However, although Knapen constructed a quite sophisticated condenser (Figure 5c) the yields were always found very weak because the inertia was concerned on days or weeks duration, not seasons. Such small yields simply reflect the fact that the mean temperature of the massive condensers goes only rarely below the air dew point temperature. As a matter of fact, Chaptal deconstructed its condensing pyramid to “not induce in errors the future generations”. Although deceiving, the massive condenser yields could, however, be improved by carrying out new studies taking e.g. into account the **underground temperature,** as for Canadian wells where inertia gives much longer condensation times, and using more sophisticated technologies (Figure 5d).

2.4. Active dew collectors

Cooling can be also ensured by an active device similar to those used in the fridges. Energy, most often electric, has to be provided. Commercial systems do exist (see e.g. www.candew.ca), the yield is on order 0.5 -1 kWh/L depending on the atmospheric conditions. However they remain quite expensive.

3. Can dew water be drunk? Chemical and biological quality

Dew water is the result of water vapour condensation. One might think it is as pure as distilled water. However, dew forms **on a substrate in an open area**. The **interactions** dew-atmosphere and dew-substrate will then give to dew water its specific chemical and biological properties.

3.1. Chemical composition

Dewcan interact with its substrate by **partially dissolving it** (e.g. zinc substrate [19]). Dew also interacts with the atmosphere. The latter is characterized by gases, which can be absorbed by water, and aerosols, which deposit on the substrate, acting as nucleation sites[11] for dew condensation and reacting with the condensed water. Then three steps govern dew chemical composition: (i) Formation of dew on dry deposition solids, (ii) dissolution of the soluble portion of the dry deposition by dew water, and (iii) sorption of gases into the dew solution.

Carbon dioxide plays a special role in the formation of acidity in the liquid phase because of its high and constant concentration. An important pathway in alkalinity (carbonate) formation goes via condensation nuclei (nucleation[11] and droplet formation) as well as aerosol scavenging. The ability to capture particulates, e.g. $CaCO_3$ from buildings or carbon particles from diesel cars, is very relevant for dew chemical composition and is strong at the beginning of the condensation process and weakened at the end. The acidity from dissolved CO_2, SO_2, and NO_x (x = 1, 2) is mostly neutralized by Mg^{2+}, Ca^{2+} and NH_4^+; sometimes a slight alkaline character is observed in dew samples. Dew events with the higher ionic concentration occur following long periods without rain. One has to note that the high concentrations in dew water of SO_2 (giving sulfuric acid), NO (nitreous acid) and NO_2 (nitric acid) is mostly of **anthropogenic origin**, in other words, coming from the **atmospheric pollution by human activities** (industry, agriculture, transportation).

Uptake of high soluble gases on atmospheric water is very fast. It will then not be affected by the short time of dew formation. When in equilibrium with atmospheric CO_2, the HCO_3^- concentration is an exponential function of the pH-value. When the pH solutions is higher than 6.35 (pKa1 of H_2CO_3), the concentration [HCO_3^-] can become important. But samples of the atmospheric multiphase system are most probably not in equilibrium with atmospheric CO_2 due to complex chemical compositions, microphysical processes and heterogeneous interactions, then the [HCO_3^-] concentration can only be obtained by analytical estimation and not deriving Henry's law [20].

Dew water composition is thus a function of both **long range convected atmosphere and locally produced gas and aerosols**. The source of anthropogenic and natural species can be found by different techniques, including air mass trajectory and stable isotope analyses. In general, regional urban pollutions have significant influence on dew water chemistry. In Table 1 are shown for sake of comparison the mean composition of dew and a low mineralized spring water (M[t] Roucous); they compare relatively well.

Table 1. Chemical composition of dew measured in Bordeaux (annual mean, from Beysens et al., 2006 [21]). It compares well with Mont Roucous spring water, which exhibits a low concentration of dissolved solids

Measurement	Dew	Mt Roucous
pH	5.88	6.0
Conductivity (µS/cm)	29 (25°C)	25 (20°C)
Na^+, mg/l	2.85	2.80
K^+, mg/l	0.25	0.40
Ca^{++}, mg/l	0.35	1.20
Mg^{++}, mg/l	0.35	0.20
Cl^-, mg/l	4.8	3.20
SO_4^{--}, mg/l	2.5	3.30
NO_3^-, mg/l	0.5	2.30
NO_2^-, mg/l	<0.01	
Dry residue (180°C), mg/l	10.3	19.0

3.2. Biological features

Biological contamination of substrates comes via **direct depositions** by insects, birds and small mammals, decay of organic debris, and atmospheric deposition of airborne micro-organisms. Contamination is generally inevitable because dew condensers are positioned in an open environment. The biological effects associated to dew are of different nature depending whether the substrate is alive, like plants, or inert.

The biological quality of dew water collected on inert substrates depends whether the microorganisms deposited on the substrate are harmless or not to human. Analyses are generally concerned with (i) aerobic bacteria as measured by colony-forming units [22] at 22 °C and (ii) at 36 °C. The first set (i) corresponds generally to harmless, vegetal microorganisms coming from the surrounding. The second set (ii) is brought mainly by insects, bird waste, mammals and human contamination. More specific investigation about human microorganisms (Enterococus, Coliforms) have also been carried out.

Microorganism contamination is fortunately limited by ultraviolet sun irradiation of dew condenser surfaces [21]. Nevertheless, the biological analysis of dew and rain shows that the World Health Organization limits can be often exceeded. **To become potable, disinfection, such as e.g. with chlorination, is therefore recommended.**

4. Biological sterilization by dew condensation

The fact that condensation can occur everywhere on a substrate, even in areas of difficult access, can be used to **disinfect medical chambers and instruments** (e.g. endoscopes) provided a sterilizing or antiseptic agent is added in the vapour

(Marcos-Martin et al., 1996 [23]). Such additives are chemical vapours (e.g. ethylene oxide, formaldehyde, chlorine dioxide or hydrogen peroxide). Sterilization is indeed the result of complex chemical reactions involving alkylation or oxidation and reduction reactions, which produce free radicals such as the **hydroxyl radical**, one of the most powerful oxidants.

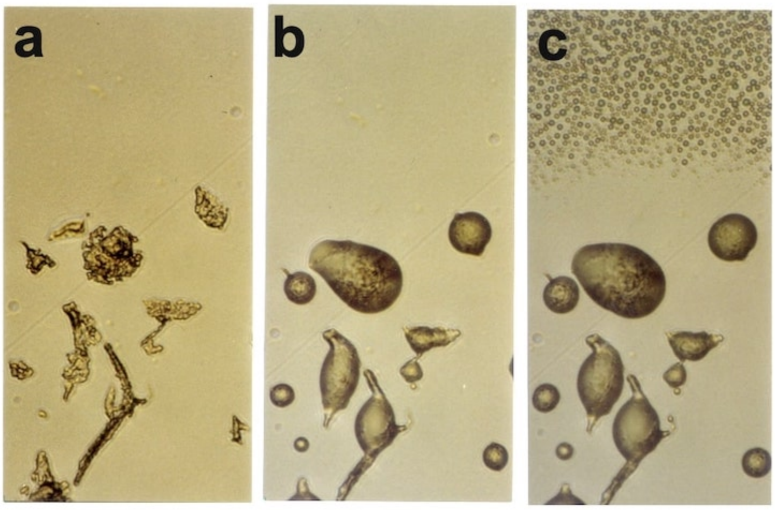

Figure 6. Lyophilized spores of Bacillus macerans on silanized glass. Experimental conditions: air saturated with water at 37 °C (ps = 6.7 kPa), substrate maintained at 18°C and flow rate 10·6 m3s-1. Time after start of vapour flux: (a) 0s ; (b) 0.5s; (c) 3s.). [Source : Photo D.Beyssens]. In (b) organic materials are wet while the substrate remains dry.

In Figure 6 is shown condensation on a substrate (glass coated with fluorochlorosilane FClSi) where water droplets exhibit a 90-110° contact angle. On the substrate are initially deposited lyophilized spores of Bacillus macerans (Figure 6a). When air saturated with water at 37 °C is sent on the substrate, condensation initially occurs only on the spores (Figure 6b). Later on (Figure 6c), condensation can be visible on the bare substrate, with region of inhibited nucleation[11]around the wetted spores. This phenomenon is typical of hygroscopic materials as e.g. droplets of NaCl water solutions where the saturation pressure is lower than pure water droplet at the same temperature. One notes that if water vapour were stopped in Figure 6b stage, no condensation on the substrate would have occurred while the microorganisms were however wet with water (and sterilizing additives if included in the vapour). This process with invisible condensation is called "microcondensation". Sterilization by humid air plus additives or water vapour plus additive without air is currently applied by some companies to disinfect hospital rooms and sterilize surgery instruments (see e.g. Advanced Sterilization Products [24] and Bioquell [25]).

5. Messages to remember

Dew is often misleadingly viewed as a form of precipitation and **confounded with fog**. Natural dew has also **to be differentiated from water condensation** on the cold walls of caves and humid room where cooling comes from the wall thermal inertia.

Dew yield is primarily **limited by the available cooling energy**, which practically does not exceed about 100 $W.m^{-2}$, leading to a theoretical maximum yield on order of 1 $L.m^{-2}$ per night.

Natural dew can give a **non-negligible contribution to the water budget** and additional water to plants and desert animals, not only in arid and semi-arid areas, but also during dry summer seasons where drought can occur for more than weeks or months.

Radiative dew harvesting for human use has recently come to near achievement status due to better understanding of associated physics and thermodynamics, the combination of new materials and condenser shapes, conical, pyramidal, origami.

The **chemical properties** of dew water come from the chemicals (gases and aerosols) present in the atmosphere in the vicinity of the condenser. It can also be connected to interaction with the condensing substrate itself.

Biological contamination of dew water originates from spores and bacteria of vegetal, animal and human origin. It is of atmospheric origin or coming from direct deposition by insects, birds, small mammals, human and airborne microbes. Such contamination is generally inevitable because dew condensers are placed in an open environment. It means that dew water **should be disinfected for drinking use**.

Sterilization by dew. In a similar way of dew condensation, but indoor, sterilization of medical instruments and hospital rooms can be carried out by condensing water with specific sterilizing elements.

Notes and references

Cover Image. [Source : https://pixabay.com/ - Royalty free image]

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[22] COLONY-FORMING UNIT is a unit used in microbiology to quantify the number of micro-organisms present in a given medium. After having taken samples from the medium, cultures are made under specific conditions on a medium able to develop the micro-organisms that form colonies, which can be counted.

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[26] RADIATION is the emission of energy by electromagnetic waves.

[27] STATES OF MOLECULAR EXCITATIONS: An excited state of an atom or a molecule is a quantum state with a higher energy than the minimum, ground state (that is, more energy than the absolute minimum). Excitations by e.g. the absorption of light (a photon) increase the energy level above a chosen starting point, the ground state or an already excited state. The return to a less excited state corresponds to the emission of a photon (light) whose wavelength depends on the difference in energy of the two states. For thermal excitation at room temperature, the range of energy corresponds to infra-red wavelengths

[28] THE ATMOSPHERIC BOUNDARY LAYER comprises the lowest part of the atmosphere extending from the ground). It is the place where ground and atmosphere exchange radiative, sensitive and latent heats (https://www.encyclopedie-environnement.org/physique/pression-temperature-et-chaleur/). It extends until where cumulus clouds form, which marks the commencement of the free atmosphere. In this layer many physical quantities (air flow velocity, temperature, humidity…) display rapid and turbulent fluctuations and vertical mixing is strong. The boundary layer thickness, h, can range from tens of meters to a few km and varies with time and can be expressed as where h is in km and T_a is the air temperature and T_d the dew point temperature near the ground.

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