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SPECIAL ISSUE: ATMOSPHERIC ELECTRICITY AND BIOMETEOROLOGY

Glossary on atmospheric electricity and its effects on biology

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Abstract
There is an increasing interest to study the interactions between atmospheric electrical parameters and living organisms at multiple scales. So far, relatively few studies have been published that focus on possible biological effects of atmospheric electric and magnetic fields. To foster future work in this area of multidisciplinary research, here we present a glossary of relevant terms. Its main purpose is to facilitate the process of learning and communication among the different scientific disciplines working on this topic. While some definitions come from existing sources, other concepts have been re-defined to better reflect the existing and emerging scientific needs of this multidisciplinary and transdisciplinary area of research.

Keywords Atmospheric electricity phenomena · Atmospheric electric field · Biological effects · Biometeorological profile · Glossary

Introduction

There is emerging evidence that atmospheric electric field (AEF) variations may interfere with biological processes at multiple scales, ranging from nanomaterial charges to global scale phenomena such as Schumann resonances (SR) of the Earth-ionosphere cavity (for review, see Hunting et al. 2020; Cifra et al. 2020; Price et al. 2020). The inclusion of atmospheric electricity is therefore becoming progressively important in studies on a wide variety of environmental processes. However, linking atmospheric electrical processes with biological processes requires the consideration of concepts and methodologies from disparate scientific disciplines, ranging from meteorology and atmospheric physics to biological and medical sciences.

Since multidisciplinary and transdisciplinary studies can only be developed if basic concepts for one discipline are shared in a simple way with other disciplines (from social sciences to data sciences), basic descriptions about some terms are demanded to facilitate integration of knowledge in common research. Therefore, we present here a glossary of terms relevant to those seeking an understanding of atmospheric electricity and its links to biological systems. By following a conceptual map that identifies key scientific disciplines and including both basic and more complex concepts, we hope to assist and reinforce future efforts in studying the coupling of atmospheric electricity and biological systems.

The conceptual frame

The effects of atmospheric electricity on biological organisms refer to the study of complex multidimensional systems (physical, biological, environmental, technical, computational, etc.) and their mutual interactions. A multidisciplinary and transdisciplinary approach is taken for this purpose, and a new conceptual scientific frame is developed in order to organize these interactions. Figure 1 presents a basic scheme with the existing interactions between different conceptual entities that require consideration in the study of bioeffects of electric and

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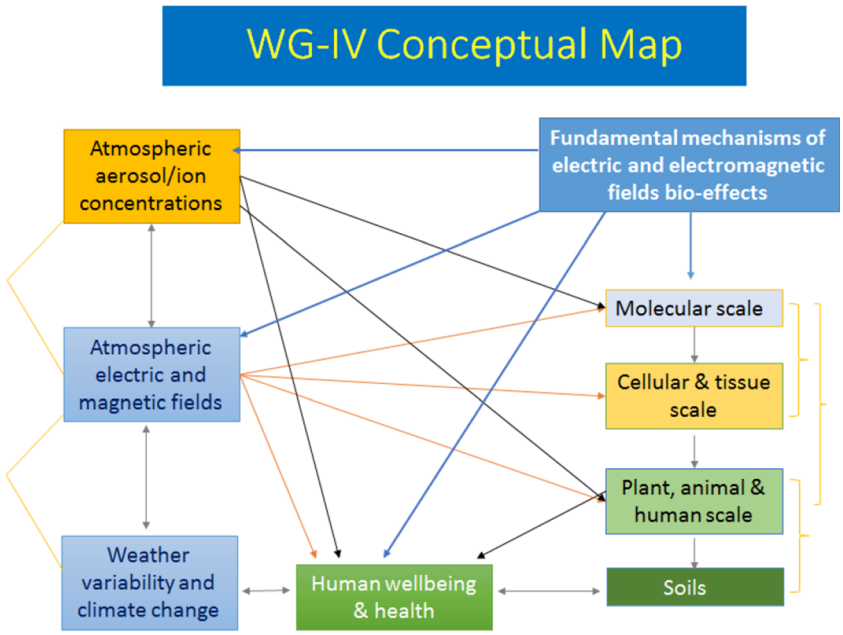

Fig. 1 Conceptual frame of the Working Group IV of the COST Action 15211

electromagnetic fields at multiple temporal and spatial scales. In this context, it is important to realize that atmospheric electromagnetic phenomena are coupled to other physical, chemical, and biological processes in the lithosphere and atmosphere, as well as the solar and cosmic system (Hayakawa et al. 2004; Cifra et al. 2020; Rycroft et al. 2000; Singh et al. 2007; Ross and Chaplin 2019).

The global electric circuit (GEC) is a central coupling node between various processes. Since the GEC is powered by lightning discharges, weather variability and climate change which affects the occurrence of lightning storms exert a direct influence on the atmospheric electric fields (AEF). Atmospheric aerosol and ion concentrations affect the conductivity of the air, and thereby the local values of AEF. The changes of aerosols and ion concentrations may also affect organisms at different scales from the molecular to human well-being level (Pöschl 2005). Likewise, soil conductivity, determined by water and chemical content and the soil grain structure, is probably an important factor influencing effects of AEF on subsurface environments.

The mechanisms of how atmospheric electric fields act on organisms are dictated by the laws of physics, regardless of their source (i.e., natural or human-made). This approach enables us to potentially harness deep insights into possible biological effects of AEFs by looking into the large body of literature devoted to mechanisms of artificially generated (man-made) electromagnetic fields (Repacholi et al. 1999; Cifra et al. 2011, http://ieee-emf.com/).

Consequently, in order to understand the biological effects of electromagnetic fields, one has to follow a multiscale approach to see how the direct effect of electromagnetic (EM) fields on molecules leads to responses at the cellular and organismal scales (Apollonio et al. 2013). The highly structured and functional complexity present in organisms is necessary for a biological response to appear, as it happens, for example, in a cellular membrane. There, it is the integrative property of the membrane, its electrical insulation capability and size (several orders of magnitude larger than the size of individual constituent biomolecules: phospholipids and proteins), which determines the response to an external electric field (Tsong and Astumian 1986). Similarly, on the tissue and whole organism scale, there are physical and biological aspects which might determine the response of organisms to the EM field and cannot be reduced to their molecular content. Therefore, we believe that an appropriate approach to AEF bioeffects needs to consider all necessary elements in the conceptual scheme.

The conceptual map codes

Map codes of potential research topics were first defined in order to assign physical terms and parameters of relevance. This list of map codes presents a state-of-the-art list of relevant topics that is not meant to be complete and should be continuously expanded and improved as new topics may emerge, considering in particular that the scientific meaning of many terms can vary substantially depending on the academic discipline they refer to. Hence, both the map codes and the glossary itself provide open lists to be used as a reference with the possibility of expanding its use. These map codes could also play a key role in the future development of a relevant ontology.

1. Atmospheric aerosol/ions concentration and size
2. Atmospheric electric and magnetic fields
3. Electric/electromagnetic field bioeffects at molecular scale
4. Electric/electromagnetic field bioeffects at cellular and tissues scale
5. Electrostatic and electromagnetic fields in soils
6. Electric/electromagnetic field bioeffects in plants
7. Electric/electromagnetic field bioeffects in animals
8. Electric/electromagnetic field bioeffects in humans
9. Space weather
10. Bioelectrical indices
11. Radioactivity
12. Atmospheric global electric circuit
13. Atmospheric electricity—lightning
14. Solar, magnetospheric, and ionospheric bioeffects
15. Electrical properties of the Earth's surface
16. Electrical properties of the Earth's atmosphere and ionosphere
17. Geographic sciences
18. Biometeorology and electric/electromagnetic fields
19. Electric/electromagnetic fields and public health
20. Others

Glossary

Absorption in blood

Conceptual map code: 1, 4, 7, 8

The movement of material into blood regardless of mechanism. Generally, applies to dissociation of particles and the uptake into blood of soluble substances and materials dissociated from particles. Includes movement of ultrafine particulate material (ICRP 1994), e.g., nanometer-size particles.

AC global electric circuit

Conceptual map code: 2, 3, 4, 5, 6, 7, 8, 12, 15

Alternating electric and magnetic fields and currents (AC), produced naturally by lightning in the extremely low frequency (ELF) radio range that are observed globally, linked to Schumann resonances (Schumann 1952, Volland 1995).

Action potential

Conceptual map code: 4, 5, 6, 7, 8

Change in polarity at a specific location along the cell membrane. This depolarization is propagated in adjacent locations across the axon or muscle membrane (Hodgkin and Huxley 1952).

Acute effect

Conceptual map code: 1, 8

A health or physiological effect that occurs suddenly over hours or days, for example, lung inflammation resulting from inhalation exposure.

Adiabatic process

Conceptual map code: 20

A thermodynamic process taking place in a system without transfer of heat or matter to (from) the system from (to) its environment. In this case, the system is said to be adiabatically isolated from its surroundings (Sontag et al. 2003).

Aerodynamic diameter

Conceptual map code: 1, 8

Aerodynamic diameter is defined as the diameter of a sphere of a given density that settles at the same terminal velocity as the particle of interest (ICRP 1994).

Aerosol

Conceptual map code: 1, 5, 6, 7, 8

Solids and/or liquid particles suspended in the air acting here as a carrier gas (WHO, 2017). Aerosol particles in the atmosphere range in diameter from 1 to 1 mm and have their origin in both natural and anthropogenic processes (Wallace and Hobbs 2006).

Aerosols charge distribution

Conceptual map code: 1

The probability that a charged aerosol (or large ion) of a given mobility has a given charge. For ambient aerosols, this is typically skewed towards slightly negative charges, as negative small ions have higher mobility and therefore are more likely to attach to atmospheric molecules. Sources of unipolar space charge (e.g., high-voltage power lines) can affect the charge distribution on an aerosol population (Hinds 1982; Wiedensohler 1988).

Aerosol dynamics

Conceptual map code: 1

Different processes that can modify the number, size, distributions, and other physical properties of atmospheric aerosol particles. These processes mainly include nucleation, coagulation, condensation, evaporation, and wet and dry scavenging as well as horizontal and vertical turbulent transport processes (Seinfeld & Pandis, 2006).

Aerosol growth rate

Conceptual map code: 1

Describes how fast aerosol particles/clusters grow in size, and is typically given in nm/h. Aerosol particles in the atmosphere enlarge via condensation and coagulation. It is usually difficult to distinguish between the contributions of these two processes to the particle growth based on ambient observations; therefore, the growth rate (GR) obtained from ambient measurements often represents the overall growth rate (Kulmala et al. 2012).

Agglomerate

Conceptual map code: 1, 5, 6, 7, 8

A collection of weakly bound particles or aggregates where the resulting external surface area is equal to the sum of the surface areas of the individual components. An aggregate is a particle comprised strongly bound or fused smaller particles (EC-GPHSW 2013).

Air ion spectrometer

Conceptual map code: 1

A magnetic field force-based device measuring the size distribution of air ions. An (air ion spectrometer) AIS consists of two differential mobility analyzers, one for measuring positive ions and the other for measuring negative ions (Mirme et al. 2007; Laakso et al. 2004).

Air-Earth current

Conceptual map code: 1, 2, 11, 12, 15, 16

Electric current, which under fair weather (FW) conditions, flows down from the positively charged atmosphere to the negatively charged Earth's surface, i.e., the current of the global atmospheric circuit flowing through the circuit's load (Wilson 1906; Chalmers 1949; Israël 1973; MacGorman and Rust 1998).

Air pollution

Conceptual map code: 1, 20

Air pollution is the presence of gasses, particles (organic and inorganic), and biological molecules in the atmosphere, especially those that do not occur naturally or occur naturally at much lower quantities (Vallero 2014). The term is mostly referred to substances caused by human activities that can cause undesirable effects to human health, plants, ecosystems, or structures.

Airborne ultrafine particles

Conceptual map code: 1, 8

The smallest fraction of ambient particulate matter, defined as airborne particles with a diameter in the nanoscale range. The term is used when referring to naturally occurring nanomaterials (EC-GPHSW 2013).

Alpha radiation (ionizing radiation)

Conceptual map code: 1, 11

Corpuscular radiation resulting from the radioactive decay of an atom emitting an alpha particle, i.e., a helium nucleus (composed of two protons and two neutrons). The effective travel distances of alpha particles in air are small (a few cm), and they cannot penetrate directly in the human body. However, if inhaled or ingested, alpha particles can cause serious cellular damage (Sollazzo et al. 2017).

Alveolar-interstitial region

Conceptual map code: 1, 8

Consists of the respiratory bronchioles, alveolar ducts and sacs with their alveoli, and interstitial connective tissue; airway generations and beyond (ICRP 1994).

Atmospheric discharge

Conceptual map code: 13, 16

Atmospheric discharge, or lightning (intra-cloud, inter-cloud, cloud-to-cloud, or cloud-to-ground) discharge, is a high-current transient flow of electricity in the atmosphere. It is caused by electrostatic processes caused by large electric potential gradients building up inside clouds due to increasing charge separation between water and ice particles and large potential gradients between the cloud base and the ground (Rakov and Uman 2002).

Atmospheric turbidity

Conceptual map code: 1

A measure of the amount of atmospheric aerosols that determines the transparency of the atmosphere. The more aerosols are present in the atmosphere, the higher the intensity of scattered sunlight, the higher the reduction of the transmission of direct sunlight, and the higher the turbidity. It expresses the attenuation of the solar radiation that reaches the Earth's surface under a cloudless sky which describes the optical thickness of the atmosphere. Atmospheric turbidity is a convenient parameter frequently used to estimate the optical characteristics of aerosols (Djafer and Irbah 2013, Guermard 1998).

Atmospheric electric field

Conceptual map code: 2, 3, 4, 5, 6, 7, 8, 12, 16

The electric field in the atmosphere (AEF) at any specified point in space and time. In areas of fair weather, the atmospheric electric field near the Earth surface is normally about 130 V/m and this value decreases in magnitude with increasing altitude, falling for example, to about 5 V/m at an altitude of about 10 km (Imyanitov and Chubarina 1967, Chalmers 1949, Israël 1973).

Atmospheric ions

Conceptual map code: 1

The term atmospheric ions, called also air ions, refers to charged molecular clusters that exists in the dense lower atmosphere where free electrons and single molecular ions cannot survive under steady state conditions. Primary sources of air ions are gamma radiation, radon decay, and cosmic radiation (Arnold 1986; Hursikko et al., 2011; Junninen et al., 2010).

Atmospheric new particle formation

Conceptual map code: 1

The production of aerosol particles in the ambient air from gaseous precursors, followed by the subsequent growth of these newly formed particles. Photochemical reactions in the gas phase are believed to trigger the initial step of atmospheric new particle (NPF) (Dal Maso et al. 2005).

Atmospheric potential gradient

Conceptual map code: 2, 4, 12, 13, 14, 15, 16

This term defines the atmospheric electric field. Typically, it is positive (downward) in fair weather conditions. A positive PG denotes current flowing downward. An increase or decrease in electric potential occurs along a line between two points, i.e., it is the rate of change of electrical potential with distance. The PG is the most common variable for characterizing atmospheric electricity in terms of the electric potential difference between an elevated reference point and the Earth's surface. In biology, the rate of change of electric potential with respect to distance in the direction of greatest change is across a cell membrane (Chalmers 1949; Imyanitov and Chubarina 1967; Israël 1973).

Auroral electrojet

Conceptual map code: 9, 14, 16

Large horizontal currents that flow in the E (dynamo) region maximizing near 110 km of the ionosphere near the northern and southern polar circles. They are auroral zone ExB electron currents, and when they expand into the lower or higher latitudes during substorm times, it is because the auroral oval expands accordingly (Rishbeth and Garriot 1969). The auroral electrojet currents are the strongest in the ionosphere because the conductivity and the horizontal electric field in the auroral ionosphere are much larger than those at other, non-auroral, latitudes.

Beta radiation (ionizing radiation)

Conceptual map code: 1, 11

Energetic particle radiation resulting from the radioactive decay of an atomic nucleus, emitting electrons, or positrons, known as β-particles. This radiation is a source of ionization production in the lower atmosphere. The travel distance of beta radiation in air (up to a few meters, depending on the β-particle energy, typically about 0.5 MeV) is larger of that for alpha particles and therefore is capable of penetrating into the human skin. However, the main risk to human health is associated with internal emission of beta particles coming from ingested radioactive material (L'Annunziata 2016).

Binary homogeneous nucleation

Conceptual map code: 1

Binary homogeneous nucleation (BHN) is an aerosol process that involves two substances in the lower atmosphere, which can condense simultaneously to form a solution droplet. A typical BHN example is the nucleation of sulfuric acid (H_2SO_4) and water vapor (H_2O). This process can be efficient in removing trace gasses from the atmosphere through gas-to-particle conversion (Mirabel and Jaecker-Voirol 1988).

Bioaerosol

Conceptual map code: 1

An aerosol of biological nature, where some living organisms (like viruses, bacteria, or fungi) or more complex products of organisms (like fungal spores and pollen) are attached to an aerosol particle (Hinds, 1999).

Bioelectricity

Conceptual map code: 3, 4, 6, 7, 8, 10

Electric potentials and currents present within living organisms. Bioelectric potentials are generated by a variety of biological processes and generally range in strength from one to a few hundred millivolts.

Bioelectromagnetics

Conceptual map code: 3, 4, 6, 7, 8, 10

Interaction processes based on electromagnetic field forces inside living tissues and organisms. Bioelectromagnetics deal

with biological effects and applications of electromagnetic fields that range in frequency from 0 Hz (static fields) to the teraHertz waves such as visible light (Schwan 1999).

Biometeorological data infrastructure

Conceptual map code: 8

A complex platform formed by a mainframe computer, a biometeorological model, a relational database management system, data procedures, communication protocols, different software packages, users, datasets, and mobile applications in order to analyze the impact of different atmospheric variables on living organisms in order to define their specific vulnerability to their variability and change (Fernandez de Arroyabe, 2017).

Biometeorological profile

Conceptual map code: 8, 15, 17, 18

The biological answers, in terms of well-being, that a living organism (animal, plant, or human being) experiences through time and space in relation to changes and variability of multiple atmospheric factors such as solar radiation and atmospheric electric field. A specific profile can be defined for each variable and living organism. It is a graphical characterization of the physical and psychological reactions of living organisms, including humans, to the variability and change of a specific atmospheric factor over a period of time (Fernandez de Arroyabe, 2017).

Blood pressure

Conceptual map code: 7, 8

The pressure of blood in the arteries of mammals, including humans. The blood pressure has two main components: an upper value (systolic), and a lower value (diastolic), the background pressure always present in the artery. The upper value is the pressure caused by the actual heartbeat. Some studies suggest that Schumann resonances and geomagnetic activity can influence blood pressure (Mitsutake et al. 2005; Palmer et al. 2006).

Blue/gigantic jet

Conceptual map code: 2, 12, 13, 16

Blue jets (BJ), gigantic jets (GJ), and other jet-type TLE phenomena shoot up to different heights from the tops of thunderclouds. These streamer-type discharges are driven by an imbalance of charges in the thundercloud. Their color is predominantly white and blue close to the thundercloud but becoming red in higher air regions. The height that a jet can reach depends on the rate the charge imbalance in the top of the thundercloud. Gigantic jets may reach up to 90–95 km, i.e., to the bottom of the ionospheric E layer at night. Jets are the least frequently observed type of TLEs; sprites are more common. See also TLE (Pasko et al. 2012; Soula et al. 2011).

Blowing dust

Conceptual map code: 20

Dust picked up locally from the surface of the Earth and blown about in clouds, or sheets, causing a hazy atmosphere. Classed as a lithometeor and is encoded BLDU as an obstruction to vision in an aviation weather observation (METAR). Blowing dust may completely obscure the sky; in its extreme form, it is called a dust storm. The existence of a layer of stable air aloft tends to stop the vertical transport of dust by eddies. There is then a sharply defined upper limit to the dust layer. It sharply enhances the aerosol concentration and alters atmospheric conductivity.

Breakdown/air breakdown

Conceptual map code: 2, 16

The process by which electrically stressed air or any other dielectric medium is transformed from an insulator into a conductor. Breakdown involves the acceleration of electrons up to the ionization potential in the electric field imposed by the thundercloud, and the subsequent creation of new electrons that avalanche and expand the scale or enlarge the volume of enhanced conductivity. Breakdown precedes the development of lightning. The electric field necessary to produce breakdown is called breakdown field (Soula et al. 2011).

Carnegie curve

Conceptual map code: 2, 12

Average diurnal variation of the atmospheric electric field at ground level, first obtained from measurements at sea from the research vessel “Carnegie” of the Carnegie Institution of Washington in the first half of the twentieth century. It is the diurnal (universal time) variation in the atmospheric electric field (maximum around 19 UT and minimum around 03 UT). It is globally independent of the measurement position (Parkinson and Torreson 1931; Harrison 2013).

Cellular respiration

Conceptual map code: 4, 5, 6, 7, 8

Cellular respiration is a process whereby energy from food is captured and stored into a molecule, namely adenosine triphosphate (ATP). Cellular respiration relies mainly on redox reactions that take place within cells and their membranes. The reactions involved in respiration are catabolic reactions, which break large molecules into smaller ones, releasing energy in the process. The final acceptor of electrons during

aerobic respiration is molecular oxygen, which is used by animals, while various bacteria use a variety of acceptors other than oxygen, for instance nitrates and sulfates, often referred to as anaerobic respiration (Rich 2003).

Charged nanoparticles

Conceptual map code: 1

Particles with diameters between 1 and 100 nm that are electrically charged. These charge carriers are stable enough under ambient atmospheric conditions and can grow further in size, provided that the ambient conditions remain unchanged (Kulmala et al. 2014).

Charges in clouds

Conceptual map code: 1, 2

Electric charge is a physical property of matter that causes it to experience a force when placed in an electric field. Separation of positive and negative charges in a thundercloud is the initial cause of a lightning strike. A cloud (or parts of the cloud) has non-zero net total charge. Some highly charged clouds such as cumulonimbus create the optimum conditions for lightning discharges to occur during a thunderstorm. Charged layers exist at the edges, tops, and bottoms of stratiform (layer) clouds (Imyanitov and Chubarina 1967; MacGorman and Rust 1998).

Circadian rhythm

Conceptual map code: 5, 6, 7, 8

Circadian rhythm is any biological process that displays an endogenous oscillation of about 24 h. These 24-h rhythms are driven by a circadian clock and they have been widely observed in various living organisms. Some studies show that they can be affected by natural weak electric fields (Wever 1973).

Clearance

Conceptual map code: 1, 8

The removal of aerosol from the respiratory tract by particle transport and by absorption into the blood (ICRP 1994). Changes in atmospheric electric conditions can be related to the amount of material inhaled and eliminated from the respiratory system of a living organism if the role of the charge becomes important in the deposition process.

Climate services – global framework for climate services (GFCS)

Conceptual map code: 8, 15, 17, 18

The development and incorporation of science-based climate information and prediction into planning, policy, and practice on the global, regional, and national scale. Climate services provide and use climate and meteorological information in a way that assists decision-making by individuals and organizations in different fields such as water, food, energy, risk, and health. Such services require appropriate engagement along with an effective access mechanism and must respond to user needs (GFCS 2020).

Cloud condensation nuclei

Conceptual map code: 1

Aerosol particles (condensation nuclei) that can activate at a given supersaturation and form into cloud droplets or cloud ice particles (Seinfeld and Pandis 2016).

Cloud generator

Conceptual map code: 12, 15

A single electrically charged cloud or all such clouds, which generate an electric current that adds to the current generated by thunderstorms flowing in the global atmospheric electric circuit. Charged clouds bring charge to the ground via raindrops and thereby contribute to the charging of the GEC (Wilson 1921; Mach et al. 2011).

Cloud-to-ground lightning –CG, +CG

Conceptual map code: 13

Lightning flash in which one or more cloud-to-ground return strokes are produced. A stroke is one impulsive discharge in which the polarity of the cloud charge transferred to the ground determines the stroke (or flash) polarity.

A discharge which transfers the positive/negative charge from the cloud to the ground, forming the downward branching pattern. It represents the most common type of lightning (Rakov and Uman 2002).

Cluster ions

Conceptual map code: 1

Positively or negatively charged molecular clusters composed of up to 100 molecules of two or more monomers, e.g., $HSO_4^-.H_2SO_4$, $HSO_4^-.(H_2O)_n$ (Harrison and Tammet 2008).

Coagulation sink

Conceptual map code: 1

Quantifies the loss rate of particles of a certain size via coagulation with other aerosol particles and via self-coagulation. It has units of $cm^{-3}\ s^{-1}$ (Dal Maso et al. 2002).

Condensation sink

Conceptual map code: 1

Measures the capability of aerosol particles in the atmosphere to accommodate condensable vapors, which is derivable from the number size distributions of aerosol particles. It is expressed in units of cm^{-3} s^{-1} (Dal Maso et al. 2002).

Conduction current

Conceptual map code: 2, 11, 12

Electric current determined by the conductivity of the air and the electric field according to Ohm's law.

Convection current

Conceptual map code: 2, 12, 16

Electric current carried by ions moving due to thermal convection of air. If the moving parcel of air is electrically neutral, no current is produced by its movement. However, in volumes of air where charges have been separated (e.g., in charged clouds), their movement by thermal convective currents will result in a convection current.

Cosmic rays

Conceptual map code: 1, 11, 16

High-energy charged particles (mostly protons with some alpha particles) that reach the Earth from outer space, interact with the nuclei of atmospheric constituents, and generate collisionally secondary reaction products in the atmosphere. Radioactive nuclei produced by cosmic ray interactions with nuclei of atmospheric constituents are called cosmogenic radionuclides (UNSCEAR 2016). The collisional process of converting atmospheric atoms or molecules into ions, or the change of an ion to another ionic form, is called cosmic ray ionization (Bazilevskaya 2000; Daintith and Gould 2006).

Cumulonimbus

Conceptual map code: 20

Heavy and dense, very tall towering clouds. The upper part often spreads out in the form of an anvil. Intense upward currents carry water vapor upwards in a cumulonimbus cloud. During this process, intense separation of positive and negative charges occurs in the developing cloud droplets and ice particles of different sizes; hence, these clouds can produce intense lightning. These clouds play a key role in the global electric circuit (WMO 2017).

D region

Conceptual map code: 9, 14, 16

The D region, called also D layer, is the bottom side region of the ionosphere between 60 and 90 km where electron densities are small (actually D region nearly disappears during the night) and the charge particle motions are controlled by collisions with the neutrals, that is, both electrons and ions are strongly collisional. The D region ionization is mainly due to the strong solar Lyman-series hydrogen radiation and the most energetic solar X-rays. It is the only region of the ionosphere where there exist also negative ions. The D region or D layer reflects ELF and VLF waves and absorbs strongly during daytime medium frequency MF and high frequency HF radio waves (Rishbeth and Garriot 1969).

Denitrification

Conceptual map code: 5, 6, 15

Denitrification is the unique pathway whereby oxidized nitrogen (usually in the form of nitrate, NO_{3-}) in the terrestrial biosphere is reduced by denitrifying bacteria into less oxidized forms and ultimately to atmospheric N_2. It occurs in terrestrial and marine environments in settings where oxygen concentration is reduced. Denitrification is also significant as the major source of atmospheric N_2O, an important greenhouse gas (Ambus 2015).

Deposition

Conceptual map code: 1, 7, 8

With regard to the respiratory track, it refers to the initial processes determining how much of the aerosol in a human's inspired air remains behind after expiration. Deposition of material may occur during both inspiration and expiration. The deposition in a region of the human respiratory tract system is expressed as a fraction of the number or activity of particles of a given size that are present in a volume of ambient air before inspiration (ICRP 1994).

Differential mobility analyzer

Conceptual map code: 1

One of the most commonly used devices to classify the sizes of aerosol particles between 1 nm and 1 um in diameter. The device is based on the electrical mobility of particles (Kulkarni et al. 2011).

Differential/scanning mobility particle sizer

Conceptual map code: 1

A type of setup to measure the number size distributions of aerosol particles. Aerosol particles are initially brought to an equilibrium charging state prior to size segregation in a differential mobility analyzer (DMA). Aerosol particles of a certain

size selected by the DMA are then grown and counted by a condensation particle counter (Wiedensohler et al. 2012).

Direct solar radiation

Conceptual map code: 6, 14

The electromagnetic radiation emitted from the sun that reaches the Earth's surface directly, that is, without being absorbed by the atmospheric constituents through molecular dissociation and photoionization, and scattered or reflected by clouds and aerosols (Liu 2002).

Dosimetry and microdosimetry

Conceptual map code: 4, 7, 8

Evaluation of the electromagnetic fields induced in animals, tissues, and cells (Liberti et al. 2009).

Earth-ionosphere waveguide

Conceptual map code: 2, 12, 13, 15, 16

The surface of the Earth and the lower ionosphere are relatively good conductors while the air between them can be considered a dielectric (insulating) layer. This system forms a waveguide for electromagnetic waves which, depending on their frequency, are reflected from the conductive boundary regions and propagate laterally away from their source (e.g., lightning).

The Earth-ionosphere waveguide (EIWG) forms the closed Earth-ionosphere cavity for low frequency electromagnetic waves (e.g., VLF and ELF radio waves), which, in principle, cannot propagate through the conducting boundaries. The quasi-spherical shell geometry of the cavity makes it possible for electromagnetic resonances to develop. This happens when radio waves propagate all around the Earth (this is possible only for ELF waves which are not severely damped during their propagation) and when the wavelength of the waves is an integer multiple of the circumference of the Earth so that constructive interference can occur, i.e., Schumann resonances (Volland 1995, Nickolaenko and Hayakawa 2002).

Earthquake precursor

Conceptual map code: 0

Anomalous statistical or dynamical pattern in the temporal variability of electromagnetic, geophysical, or geochemical properties arising from the accumulation and subsequent release of mechanical stress of an approaching earthquake. Unambiguous association of such observable patterns with particular future earthquakes is generally not possible, which poses fundamental restrictions to individual earthquake predictability (Ouzounov et al. 2018).

Ecology

Conceptual map code: 6, 7, 8

The study of how organisms interact with each other and with their physical and chemical environment (Freeman et al. 1965).

Electric charge

Conceptual map code: 2–8, 12–16

Electric charge is the physical property of matter that causes it to experience a force when placed in an electromagnetic field. There are two types of electric charges: positive and negative (commonly carried by protons and electrons, respectively). Like charges repel and unlike attract. The electric charge of an electron is − 1e, while that of a proton is + 1e. With the absence of net charge on a particle, it is referred to as neutral. An object (e.g., a molecule, or a larger particle) can be negatively charged if it has an excess of electrons, and positively charged if it has a deficiency of electrons, or uncharged.

Electric charge of biomolecule

Conceptual map code: 1, 3

Electric charge is the physical property of a piece of matter (here a biomolecule) that causes it to experience a force when placed in an electromagnetic field. The larger the charge, the larger the force on the biomolecule due to the applied electric field. The amount of charge on the biomolecule and its parts determines the magnitude of its interaction ("sensitivity") to the electric fields, including the AEF (Winzor 2005; Ruggeri et al. 2017).

Electric field

Conceptual map code: 2–8, 12–16

An electric field (EF) is the force field that is created by electric charges. The electric field will affect a charge placed within the field by repelling or attracting it. Electric fields are created by electric charges and also by time-varying magnetic fields (Purcell and Morin 2013, Feynman 1970).

Electric potential

Conceptual map code: 1, 5, 6, 7, 8, 15, 16

An electric potential (also called the electric field potential, or the electrostatic potential) is the amount of work needed to move a unit positive charge from a reference point to a specific point inside the field without producing any acceleration. Typically, the reference point is the Earth or a point at infinity, although any point beyond the influence of the electric field charge can be used (Feynman 1970; MacGorman and Rust 1998).

Electrical mobility

Conceptual map code: 1

The term refers to both electron and ions which are forced to move in a medium under the action of an electric field. In the lower atmosphere, there are no free electrons; there we have positive and negative cluster ions. In general, the mobility is defined as the charged particle drift velocity divided by the acting electric field. The electrical mobility is proportional to the mean free path and inversely proportional to the mean thermal speed that depends on temperature according to the kinetic theory of gasses (Volland 1984; Chalmers 1949).

Electrical conductivity

Conceptual map code: 1, 5, 6, 7, 8, 15, 16

This is an essential physical quantity in atmospheric electricity. In general, the conductivity, σ, is an electrical parameter of a conducting medium that determines the current density in the medium caused by the action of an electric field; it enters the Ohm's law $\mathbf{J} = \sigma\mathbf{E}$. In the lower atmosphere where there are no free electrons, the conductivity depends on both the positive and negative (cluster) ion densities and their electrical mobilities; it takes extremely small conductivity values near the ground, of the order of $2.2 \times 10^{-14}\ \Omega^{-1}\mathrm{m}^{-1}$ (Volland 1984).

Electrical low pressure impactor

Conceptual map code: 1, 8

ELPI®+ (electrical low pressure impactor) is an improved version of the widely used and well-characterized ELPI® system. ELPI®+ enables the measurement of real-time particle size distribution and concentration in the size range of 6 nm–10 μm with 10 Hz sampling rate (Järvinen et al. 2014).

Electrical storm

Conceptual map code: 0, 13, 16

Popular term for thunderstorm. Sometimes applied to a relatively rare condition of disturbed atmospheric electric field in the lower atmosphere that arises when strong winds are blowing and there is much dust in the air, but no thunderstorm activity. Triboelectrification due to the blowing dust may charge metallic objects to such an extent that slight shocks are felt when touched (James et al. 2008).

Electromagnetic radiation

Conceptual map code: 2, 3, 4, 5, 6, 7, 8, 15, 16

It refers to the waves (or their quanta, photons) of the electromagnetic field propagating (radiating) through a medium, carrying electromagnetic radiant energy. It includes a broad variety of waves covering a broad spectrum, for example, extremely low and very low frequency waves, radio waves, microwaves, infrared, visible waves (light), ultraviolet, X-rays, and gamma rays. In space and approximately the atmosphere, EM radiation propagates approximately with the speed of light.

Electrometeor

Conceptual map code: 2, 13, 16

Any visible or audible manifestation of atmospheric electricity, most commonly lightning and thunder, but also aurora and St. Elmo's fire (WMO 2017).

Electromigration

Conceptual map code: 5

The movement of charged particles in the form of ions due to the presence of an electric or magnetic field. Electrokinetic flows can occur at low current densities, ranging from 0.025 to 5 Am^{-2}. These electric fields occur in soils and sediments due to natural potential gradients, but they are also increasingly applied to remove contaminants from soils and sediments in a process called electro-remediation. The effective ionic mobility by electromigration of a specific ion in a soil is a function of its molecular diffusion coefficient, soil porosity, tortuosity factor, and charge (Probstein and Hicks 1993).

Electron transport chain/system

Conceptual map code: 4, 5, 6, 7, 8

An electron transport chain (ETC) is a series of molecules within cells, their membranes, or in the extracellular matrix that transfers electrons from electron donors to electron acceptors via redox (both reduction and oxidation occurring simultaneously) reactions. This electron transfer results in the transfer of protons (H^+ ions) across a membrane, which creates an electrochemical proton gradient that drives the synthesis of adenosine triphosphate (ATP), a molecule used to store energy. Electron transport chains are used for extracting energy via redox reactions from sunlight in photosynthesis or, such as in the case of the oxidation of sugars, cellular respiration (White 1999).

Elves

Conceptual map code: 2, 12, 13, 16

Elves is a generic name given for a transient luminous event (TLE) in the upper atmosphere occurring between about 85 and 105 km. This is a donut-like shaped emission produced by the red-light emissions of molecular nitrogen, excited by the electromagnetic pulse transmitted upwards by an intense cloud to ground lightning stroke in a thunderstorm. Elves live

for about 1 ms and extend out horizontally up to a few hundred kilometers (Pasko et al. 2012).

Endogenous biological chemiluminescence

Conceptual map code: 3, 4, 5, 6, 7, 8

Emission of light from biological systems due to oxidative chemical reactions taking place within them. This luminescence is also called ultra-weak photon emission (UPE). Since electric fields applied to biosystems can induce oxidative and hence biological effects, monitoring oxidation due to an electric field or electrode potential is important and can be achieved via monitoring UPE (Cifra and Pospíšil 2014; Bonnafous et al. 1999; Maccarrone et al. 1998).

Extraterrestrial radiation

Conceptual map code: 9, 11, 16

Extraterrestrial radiation is the sun's EM radiation at the top of the Earth's atmosphere falling on a plane normal to the sun rays. It is expressed in irradiance units (Watts per square meter) and takes a value of 1360 W/m^2, which is called "solar constant" (Liu 2002; Gueymard 1998).

Extremely low frequency

Conceptual map code: 2

ELF refers to very long wavelength electromagnetic waves falling in the 3–3000 Hz band of the EM spectrum. ELF waves are produced naturally in the atmosphere by lightning and can travel around the Earth in the so-called Earth-ionosphere waveguide, or inside the Earth-ionosphere cavity. Please keep only one reference, for example (Price 2016).

F and E regions of the ionosphere

Conceptual map code: 9, 14, 16

The ionospheric F region is produced by photoionization caused by the incident extreme ultraviolet (EUV) solar radiation. It extends from about 160 km to more than 600 km, having its peak electron density located between 250 and 350 km. It is usually comprised two layers, a secondary one below 200 km (F1 layer) and its main layer centered about its maximum electron density height (F2 layer). The F region is taken to be a weakly ionized plasma imbedded into the much denser neutral atmosphere, called at the F region heights, the thermosphere.

The E region, or E layer, is situated below the F region between 90 and 160 km, having its ionization maximum at 110 km. The dominant ions are the molecular NO^+ and $O2^+$ ions generated by photochemical reactions driven by the sun's UV radiation. The strongest ionospheric currents are flown near the E region peak, called electrojets, e.g., the auroral and equatorial electrojets (Rishbeth and Garriot 1969).

Fair weather

Conceptual map code: 1, 12, 14

Although the term has a different meaning in general meteorology, when used in relation to AEF, it refers to weather conditions of low cloudiness, low wind speed, lack of fog and precipitation, low aerosol concentrations, and etc., which permit the study of parameters of the global atmospheric electric circuit at a particular location (Chalmers 1949, Imyanitov and Chubarina 1967, Harrison and Nicoll 2018).

Field mill

Conceptual map code: 2, 12, 13

A device measuring the electric field, based on the principle of electrostatic induction, consisting of electrodes periodically exposed (using, e.g., rotating disks) to the electric field (Israël 1973; Imyanitov 1957; Wahlin 1986).

Floral electric field

Conceptual map code: 6, 7, 8

A weak electric field exists around flowers due to a negative charge induced on the surface of plants and a positive charge in the air (Bowker and Crenshaw 2007). This electric field can change depending on the flowers' positioning to the soil (e.g., height), and plant electrophysiological properties (e.g., stem potential and surface conductivity). These static electric fields appear to have complex geometries and they are magnified (up to ~ 5 kV) around points (e.g., stigmas) or when flowers are approached by positively charged bees (Clarke et al. 2017). Floral electric fields can facilitate transfer of charged pollen and carry information relevant to the assessment of floral reward by bees (Corbet et al. 1982; Clarke et al. 2013).

Forbush decrease

Conceptual map code: 0

A Forbush decrease is a rapid decrease in the observed galactic cosmic ray intensity following a coronal mass ejection (CME). It results to decreases in secondary ion and electron production in the atmosphere all the way down to the ground, therefore causing conductivity reductions which are observed mostly above about 10 km (Forbush 1937).

Galactic cosmic radiation

Conceptual map code: 1, 11

Cosmic rays are very energetic charged particles originating from sources outside the solar system, i.e., coming from

deep space. The nucleonic component is due primarily to protons and alpha particles with energies ranging from 10^8 eV to more than 10^{20} eV (Bazilevskaya 2000; UNSCEAR 2016).

Gamma radiation

Conceptual map code: 1, 11

Electromagnetic radiation, called also gamma (γ) rays, resulting from the radioactive decay of an atomic nucleus emitting a high-energy photon (energies are above 100 keV). Gamma rays, which occupy the most energetic band of the EM spectrum (frequencies of the order of 10^{22} Hz), have much larger penetration power than those of alpha or beta radiation; therefore, they can be biologically hazardous. They penetrate the human body, causing damages to the internal organs and bones. Gamma rays are shielded for protection purposes by using dense materials, e.g., lead (Adrovic 2012; Liu 2002).

Gaseous precursor

Conceptual map code: 2, 12, 17

A gas that participates in a reaction that leads to the formation of aerosols. For example, terpenes produced by trees, when in the atmosphere, undergo a series of oxidation reactions that at some stage produce high boiling point vapors which, at atmospheric temperatures, condense and form aerosols.

Geoelectric field

Conceptual map code: 14

Electric field induced in the Earth's electrically conducting crust, mantle, and ocean by natural time-dependent geomagnetic field variations generated by dynamic processes in the Earth's geospace environment (Love and Bedrosian 2019).

Geomagnetic activity

Conceptual map code: 14

An enhancement of variations in the Earth's magnetic field observable at the Earth's surface and atmosphere and the near-Earth environment. Geomagnetic activity is commonly related to perturbations triggered by interactions of charged particle clouds embedded within the solar wind with the natural magnetic field of the Earth, in the most severe cases leading to geomagnetic storms (Hargreaves 1992, McPherron 1995).

Geomagnetic equator

Conceptual map code: 0, 2, 14

The GM equator is defined by the locus of points forming a circular periphery around the earth where the Earth's magnetic field is horizontal, that is, the magnetic inclination or magnetic dip angle is zero.

Geomagnetic field

Conceptual map code: 2, 9, 12, 14

The magnetic field that originates in the Earth's interior and extends out into space where its magnitude and direction can be modified by the solar wind. The magnitude of the geomagnetic field at the Earth's surface ranges from ~ 25 μT at the geomagnetic equator to ~ 65 μT at the magnetic poles (0.25–0.65 G) (Finlay 2010).

Geomagnetic indices

Conceptual map code: 0, 14

Variables describing the time variations of the geomagnetic field strength at the Earth's surface and in the near-Earth space environment, often on hourly time scales (Hargreaves 1992, McPherron 1995).

Geomagnetic poles

Conceptual map code: 0, 2, 14

The two positions on the Earth's surface where the dipole-like geomagnetic field lines merge so they become perpendicular to the Earth's surface. Those two points define the North and South poles of the Earth's magnetic field, where the field is taking its maximum value (Hargreaves 1992).

Geomagnetic storm

Conceptual map code: 14

A geomagnetic storm is a temporary disturbance of the Earth's magnetosphere and magnetic field caused by a more intense than usual solar wind (i.e., larger speed and density). It is common for the geomagnetic index Dst to have values below − 50 nT. Severe geomagnetic storms may have devastating effects on electrical power generation and transmission lines as well as on the performance and health of satellite instruments (Gonzalez et al. 1994; Kivelson and Russel 1995; Runge et al. 2018).

Geophysics

Conceptual map code: 5

The natural science concerned with the physical processes and physical properties of the solid Earth, the oceans, and its surrounding space environment that includes the atmosphere, ionosphere, and magnetosphere. Biogeophysics is a subdiscipline concerned with the geophysical signatures of biotic interactions with geological/geophysical media, and spans

disciplines such as geomicrobiology, biogeoscience, and biogeochemistry.

Gerdien cylinder/condenser

Conceptual map code: 1, 16

A device measuring the atmospheric ion concentration or air conductivity, consisting of two coaxial cylinder electrodes, the central one being connected to an electrometer (Imyanitov 1957; Wahlin 1986).

Global electric circuit

Conceptual map code: 1, 2, 12

The totality of electric currents flowing in a planet's atmosphere which form a closed electrical circuit from the sources (e.g., thunderstorms which act as batteries) to the fair weather atmosphere (which acts as a load) (Rycroft et al. 2000; Singh et al. 2007; Williams and Mareev 2014). The DC global electric circuit refers to direct currents and fields that are quasi-static in time produced by global thunderstorm activity and electrical shower clouds. Precipitation current relates to an electric current carried by precipitating particles such as rain (Chalmers 1949; Reiter 1985; MacGorman and Rust 1998; Odzimek et al. 2018).

Global radiation

Conceptual map code: 2, 11

The total short-wave electromagnetic radiation originating mainly in the sun that falls onto a horizontal surface on the ground. It includes both direct and diffuse solar radiation, the latter coming indirectly through reflection and scattering of sunlight in the atmosphere.

Health hazard

Conceptual map code: 1, 8

The inherent potential of a situation to cause physical or psychological harm to the health of people (WHO, 2017).

Heterogeneous nucleation

Conceptual map code: 1

Nucleation from the gas phase on a foreign surface or substance. The nucleation can be from a single species on a foreign substance (heterogeneous-homomolecular) or nucleation of two or more species on a foreign substance (heterogeneous-heteromolecular) (Seinfeld and Pandis 2016).

High aspect ratio nanoparticles

Conceptual map code: 1, 8

Particles with one or two dimensions in the nanoscale that are much smaller than in the other dimensions. Besides nanofibres, nanoplatelets (that present only one dimension in the nanoscale) are considered to be high aspect ratio nanoparticles (HARNs) (EC-GPHSW 2013).

Homogeneous nucleation

Conceptual map code: 1

Nucleation from the gas phase without a surface or without pre-existing foreign nuclei. Nucleation can be from a single species (homogeneous-homomolecular) or can be the nucleation of two or more species (homogeneous-heteromolecular) (Seinfeld and Pandis 2016).

Human bioclimatology

Conceptual map code: 9, 17, 18

The scientific discipline which seeks to understand the influence of climate and weather upon humans (Munn 1987).

Human respiratory tract model

Conceptual map code: 1, 8

The model used to estimate pulmonary deposition of atmospheric charged particles, retention, and biokinetic clearance to blood (ICRP 1994).

Inhalable fraction

Conceptual map code: 1, 8

The mass fraction of total airborne particles inhaled through the nose and mouth (ECS1 1993).

Intermediate ions

Conceptual map code: 1

Atmospheric cluster ions in the lowest atmosphere with sizes between the so-called small and large ions, having typical diameters between 1.6 and 7.4 nm. Their mobilities range between 0.034 and 0.5 $cm^2V^{-1}s^{-1}$ (Hörrak et al. 2000).

Ion balance equation

Conceptual map code: 1

An equation describing the processes of ion production, ion–ion recombination, ion-aerosol attachment, and ion-induced nucleation, thereby describing the number of atmospheric ions present in a system (Israël 1971; Harrison 2000).

Ion recombination

Conceptual map code: 1

The process by which ions of opposite polarities recombine and neutralize. The ion recombination rate coefficient is usually denoted by alpha and is of the order of 10^{-6} cm^3 s^{-1} at sea level. This process is taking place in the lower atmosphere where there are no free electrons, whereas the recombination in the ionosphere is basically between ions and free electrons (Hoppel 1969; Israël 1971).

Ion-aerosol attachment

Conceptual map code: 1

The process by which aerosols gain charge from ions. The rate at which ions attach to aerosol particles is dependent on the size of the aerosol present, the charges present on the aerosol, and the number density of ions and aerosol particles (Gunn 1954; Israël 1971).

Ion-induced nucleation

Conceptual map code: 1

Nucleation is the process that a new phase or self-organized structure appears; for example, the water in the gas phase (water vapor) inside a cloud transforms into liquid or solid (ice) phase. Ion-induced nucleation means that the presence of an ion can lower the energy barrier between particles, therefore boosting the nucleation process (Kirkby et al. 2016).

Ionosphere

Conceptual map code: 9, 12, 13, 14, 16

The ionosphere is the Earth's nearest ionized plasma region, characterized by the presence of free electrons. It extends from about 60 to more than 1000 km; its upper boundary is not defined exactly, forming the inner edge of the magnetosphere; therefore, it is highly changeable. The ionosphere is generated by photoionization processes, energized by solar EM radiation ranging from ultraviolet to X-rays. The ionosphere affects the propagation of electromagnetic waves and causes scattering of high frequency (HF) and very high frequency (VHF) radio waves. It hosts a wide range of electromagnetic phenomena and interactions with the atmosphere and magnetosphere (Rishbeth and Garriot 1969).

Ionospheric potential

Conceptual map code: 2, 12

The potential of the lower boundary of the ionosphere relative to the Earth's surface is called ionospheric potential (IP). Thunderstorms and electrified clouds act as a meteorological generator of electric potential differences which cause the ionospheric potential to be about ≈ + 250 kV with respect to the Earth's surface. Most of the potential difference occurs near the Earth's surface, i.e., in the first few kilometers. This is due to the rapid increase of conductivity with increasing height. IP variations in IP can be caused by conductivity perturbations inside thunderstorms, and solar modulated changes in cosmic ray flux, as well as other factors influencing ion production rates, such as atmospheric nuclear tests and volcanic eruptions (Rycroft et al. 2000; Markson 2007).

Ionospheric storm

Conceptual map code: 9, 14, 16

Large-scale disturbances in the F region ionosphere driven by highly variable solar energetic particle and electromagnetic wave energy inputs incident upon the Earth during periods of very intense solar activity, this is, during solar flares and coronal mass injection events. These disturbances, which represent large deviations from the "quiet-time" ionosphere, affect the ionospheric energy and particle distributions, the total electron content, and the ionospheric electric fields and current systems (Buonsanto 1999).

Isoceraunic

Conceptual map code: 2, 9

A line on a map connecting points of equal frequency (or intensity) or simultaneous occurrence of thunderstorms (lightning discharges).

Isoclinic line

Conceptual map code: 2, 14

A line on a world map connecting points of equal magnetic inclination at a given height. Magnetic inclination is the angle between the Earth's magnetic field vector and the horizontal direction in the magnetic meridional plane.

Large ions

Conceptual map code: 1

They are atmospheric aerosols with diameters in the range between 5 and 80 nm, which gained a net charge by a process called ion-aerosol attachment. Their electrical mobilities range from 0.0004 to 0.03 cm^2V^{-1} s^{-1} (Hörrak et al. 2000).

Leader

Conceptual map code: 9, 14

A hot, conducting plasma channel in a lightning flash which is electrically polarized having oppositely charged ends. The negative leader end propagates into the direction of the positive cloud charge, and vice versa. A bidirectional leader tree has zero net charge (Rakov and Uman 2002).

Lightning current/lightning flash

Conceptual map code: 2, 12, 13, 15

The electric current carried by a lightning discharge, mainly in the form of electrons. A lightning flash is an electric discharge separated from other flashes by space and time criteria. In one flash, all processes from the initial breakdown to leader growth and any strikes to the ground are included (Uman 2008).

Long wave radiation

Conceptual map code: 2

Electromagnetic radiation in the atmosphere confined in the infrared spectral band, having wavelengths between about 4.0 and 100 μm. Although there is a small part of this radiation coming from the sun, most originates from the Earth's surface which radiates as a black body at a temperature of 255 K. Long wave (LW) radiation plays a key role in the greenhouse effect because it is absorbed strongly in the atmosphere by water vapor and carbon dioxide.

Lower positive charge region

Conceptual map code: 9, 12, 14

Short-lived positive charge region just below the main negative layer in the model of the tripole structure of charges in the thundercloud.

Magnetosphere

Conceptual map code: 9, 14

Magnetosphere is a complex region surrounding the Earth that relates to the dynamic state of the Earth's magnetic field topology. Its shape, which depends on solar activity, is determined by complex coupling processes between the Earth's magnetic field, the solar wind plasma, and the interplanetary magnetic field. The particle motions and currents in the magnetosphere are governed by the laws of electromagnetism and magnetohydrodynamics (Hargreaves 1992; Kivelson and Russel 1995).

Mechanoreceptor hairs

Conceptual map code: 6, 7, 8

Hairs on the surface of most terrestrial arthropods (such as insects and spiders) that are sensitive to small, sometimes nanoscale, mechanical forces (McIver 1985).

Membrane potential

Conceptual map code: 6, 7

The difference in electric potential between the interior and the exterior of a biological cell. With respect to the exterior of the cell, typical values of membrane potential range from − 40 to − 80 mV (Alberts 2014).

Mesosphere

Conceptual map code: 0, 20

The mesosphere is the layer of the Earth's atmosphere that lies above the stratosphere. The temperature profile defines the limits of the mesosphere. Above its lower limit at about 60 km, where is the stratopause, the temperature decreasing with altitude up to the mesopause at about 90 km; there the temperature reaches 170 K, which is the lowest temperature in the Earth's atmosphere. The mesosphere is chemically the most complex region of the atmosphere (Wallace and Hobbs 2006).

Mobility distribution

Conceptual map code: 1

The ion mobility distribution measured by an air-ion spectrometer. The ion mobility is defined as the drift velocity of ions divided by an acting electric field (Hinds 1982; Hirsikko et al. 2011).

Modification of the energy spectra

Conceptual map code: 2, 12, 14

Peaks and dips, which arise in time series of count rates of surface particle detectors, due to the asymmetry of positive-to-negative fluxes of secondary cosmic rays in the terrestrial atmosphere.

Molecular ions

Conceptual map code: 1

Charge carriers in the form of monomers, e.g., HSO_{4-}, NO_{3-}, H_3O+ (Shuman et al. 2015). It refers to the lower part of the atmosphere, or the troposphere.

Nano-object and nanoparticle

Conceptual map code: 1, 8

A nano-object is a discrete piece of material with one or more external dimensions in the nanoscale, 1–100 nm (Lidén 2011). A nanoparticle is a nano-object with all three external dimensions in the nanoscale, from 1 to 100 nm. If the length of the longest and shortest axes of the nano-object differs significantly (typically by more than three times), the terms nano rod or nano plate can be used (EC-GPHSW 2013). The biological effects of atmospheric charged nanoparticles remain to be discovered.

Nanosecond-pulsed electric fields

Conceptual map code: 4, 8

Ultrashort electrical pulses, of a duration similar to that of a streamer propagating in lightning discharges, and used in some laboratories to analyze electric field interactions with biological objects (cells, tissues, etc.).

Natural radioactivity

Conceptual map code: 1, 11

Radioactivity arising from natural sources, including both primordial radionuclides in the Earth's crust and radionuclides formed from the interaction of cosmic rays with the atmosphere and during thunderstorms and lightning conditions (Reiter 1985, Kathren, 1998).

Nucleation/nucleation barrier

Conceptual map code: 1

The formation of new aerosol particles from gaseous precursors. A nucleation barrier is an effective energy barrier that prevents the gas from nucleation although it is supersaturated in the gas phase (Rogers 1979).

Primary atmospheric ions

Conceptual map code: 1

The atmospheric ions resulting from solar photoionization of the atmospheric constituents, e.g., N+, N2+, O+, and O2+, where the atomic ions here follow after the photo-dissociation of molecular ions (Shuman et al. 2015).

Protein

Conceptual map code: 3

Proteins are large biomolecules consisting of one or more long chains of amino acids. Proteins have a spatially complex distribution of electric charges in their structure. The charge distribution of proteins determines the nature and magnitude of the protein sensitivity to electric fields. Since proteins are molecules which determine life processes, one mechanism of how an electric field can act on a molecular scale is through influencing the protein dynamics and structure (Hekstra et al. 2016; Marracino et al. 2019; Chafai et al. 2019). Intense electric fields, such as generated by lightning, might be strong enough to affect protein structures.

Q-burst

Conceptual map code: 2, 13, 16

Exceptionally powerful lightning discharges produce ELF radio waves whose amplitude can exceed that of the natural ELF background noise by several times. These waves cause characteristic transient signals, Q-bursts, in the recorded time series at ELF monitoring stations. The most powerful waves can travel a few times around the Earth and may excite the lowest Schumann resonance modes for a fraction of a second (Ogawa et al. 1967, Nickolaenko 2010).

Radioactive collector

Conceptual map code: 2, 12

A device measuring the potential gradient, consisting of an electrometer connected to a conducting antenna and an alpha radiation source in the vicinity of the antenna in order to speed up the equalization of the potential of the antenna and the surrounding air (Chalmers 1949; Imyanitov 1957; Wahlin 1986).

Radon -^{222}Rn

Conceptual map code: 10, 11

Radon is a chemical element with the symbol Rn; it is a radioactive gas. It occurs naturally as an intermediate step in the normal radioactive decay chains through which thorium and uranium slowly decay into lead; radon itself is a decay product of radium. Its most stable isotope, ^{222}Rn, has a half-life of 3.8 days. Unlike all the other intermediate elements in these decay chains, radon is gaseous and easily inhaled. Radon gas is a health hazard. It is often the single largest contributor to an individual's background radiation dose, but due to local differences in geology, the level of radon gas hazard differs from location to location. Despite its short lifetime, radon gas from natural sources can accumulate in buildings, especially, due to its high density in low areas such as basements and crawl spaces. Radon can also occur in ground water in some spring waters and hot springs.

Radon progeny

Conceptual map code: 1, 11

Short-lived radioactive elements ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po which result from the radioactive decay of radon (^{222}Rn).

Read across

Conceptual map code: 1, 8

Transfer of hazard information from one material to another based on similarities between the materials (WHO, 2017).

Red sprite

Conceptual map code: 2, 12, 13, 16

Red sprites are optical flashes produced by short-lived streamer-type electric discharges in the mesosphere. These occur due to the quasi-static electric field which can build up in the mesosphere after an extremely powerful lightning discharge for a few milliseconds. The electrical current flowing

in the body of sprites can reduce the ionospheric potential by ~ 1 V (Rycroft and Odzimek 2010). Most often, several sprites occur quasi-simultaneously, sometimes in a rapid sequence (the so-called dancing sprites). There is a great variety of shapes of red sprites depending on the paths that the heads of streamer discharges explore during their development. Sprites are mostly vertical structures of length 20–50 km, while those in a sprite cluster may be scattered over an area of up to several hundred square kilometers. The color of the emission is predominantly red at high altitudes while it contains more blue when produced in lower air regions. See also TLE (Franz et al. 1990; Rodger 1999; Rakov and Uman 2002; Neubert et al. 2008; Bór 2013).

Reduction oxidation potential/oxidation reduction potential

Conceptual map code: 5, 11, 14

Reduction oxidation potential (REDOX) is the measure of the tendency of a medium such as soil or water to acquire or release electrons. The quantity of redox potential is labeled as Eh and has units of mV (Vorenhout et al. 2004, 2011). Oxidation reduction potential (ORP) is similar to redox potential, i.e., is a measure of the tendency of a chemical species to acquire electrons from or lose electrons to an electrode and thereby be reduced or oxidized, respectively. The term is used for measurements of redox potential in water, normally given in mV (Lee et al. 2006).

Respiratory particle transport

Conceptual map code: 1, 8

Processes that clear material from the respiratory tract to the gastrointestinal tract and to the lymph nodes, and move material from one part of the respiratory tract to another (ICRP 1994).

Respirable fraction

Conceptual map code: 1, 8

The mass fraction of inhaled particles penetrating to the nonciliated (i.e., hairless) airways (ECS1, 1993).

Risk of bias

Conceptual map code: 1, 8

The risk that the results of a study can be distorted due to methodological limitations such as the presence of confounders (i.e., factors causing a spurious association) (WHO, 2017).

Schumann resonances

Conceptual map code: 2

The Schumann resonances are the set of spectral peaks in the extremely low frequency (ELF) portion of the Earth's electromagnetic field spectrum. Schumann resonances are global electromagnetic resonances, generated and excited by lightning discharges in the spherical shell cavity formed by the Earth's surface and the ionosphere. Schumann resonances are the principal background signal in the ELF part of the electromagnetic spectrum and appear as distinct peaks at ELF around 7.8 Hz (fundamental), 14.3, 20.8, 27.3, and 33.8 Hz (Schumann 1952, Sentman 1995, Volland 1995, Price 2016).

Schumann resonance transient

Conceptual map code: 2, 13, 17

See Q-burst.

Secondary aerosols

Conceptual map code: 1

Aerosols that form through gas-to-particle conversion in the atmosphere (Sienfeld and Pandis 2016).

Self-potential

Conceptual map code: 5

Self-potential (SP), or spontaneous potential, is a naturally occurring electric potential difference in the Earth, measured by an electrode relative to a fixed reference electrode. SPs are usually caused by charge separation in clay or other minerals, due to the presence of a semi-permeable interface impeding the diffusion of ions through the pore space of rocks, or by the natural flow of a conducting fluid, e.g., (contaminated) groundwater flows (Revil et al. 2003).

Sensory ecology

Conceptual map code: 6, 7, 8

Sensory ecology studies how organisms acquire, process, and respond to information from their environment (Dusenbery 1992). These senses include, for instance, smell (olfaction), taste (gustation), hearing (mechanoreception), and sight (vision) as well as electro- and magnetoreception. Sensory interactions are studied as influences of sensory cues on certain physiological systems (sense organs) and resulting behaviors. Sensory ecologists aim to understand which environmental and sensory cues are more important in determining the behavioral patterns of certain species as well as the physical and chemical processes that underlie these interactions.

Shortwave radiation

Conceptual map code: 2

In atmospheric science, this refers to solar radiation in the visible, near-ultraviolet, and near-infrared parts of the spectrum, in the wavelength interval 0.4–1.0 μm. The SW radiation in the atmosphere is emitted from the sun's photosphere that radiates as a black body at a temperature of 6000 K.

Small atmospheric ions

Conceptual map code: 1

Atmospheric ions created by natural or anthropogenic processes. They rapidly undergo clustering to form hydrates and can break apart. Their mobility ranges from 0.5 to 3.2 $cm^2V^{-1}s^{-1}$ (diameter 0.36–1.6 mm) (Israël 1971; Hörrak et al. 2000). These are the ions contributing to the atmospheric conductivity.

Solar cosmic radiation

Conceptual map code: 1, 11

Solar cosmic radiation is fluxes of highly energetic charged particles, predominantly protons, accelerated in the corona and chromosphere during solar flares and coronal mass ejections. They are energized by shock acceleration processes when the solar magnetic field reconfigures itself locally through violent magnetic reconnection. Solar cosmic rays have energies ranging between 10 MeV and 10 GeV, and when they enter, the atmosphere collides with its constituents producing secondary energetic particles. They can be guided by the Earth's magnetic field to high magnetic latitudes where they produce the so-called solar portion events (SPE), characterized by enhanced ionization in the lower ionosphere, causing radio wave blackout (Miroshnichenko 2015).

Solar flare

Conceptual map code: 9, 14, 16

A bright region that develops abruptly in a confined area on the sun's corona. It is generated when magnetic energy that builds up in the solar atmosphere is suddenly released. Solar flares become a source of very energetic particles, strong electromagnetic wave emissions and mass ejections, all emanating outwards from the sun into the surrounding space (Tandberg-Hansen 2009; Priest 1995; Hundhausen 1995; Shibata and Magara 2011; GSFT n.d.).

Solar storm

Conceptual map code: 9, 14

A solar storm is a large-scale dynamic disturbance that erupts in the heliosphere, propagating outwards in the form of intense electromagnetic emissions, highly energetic particle fluxes, and hot solar wind plasma. It affects the entire solar system, including the Earth and its magnetosphere, and is the cause of violent space weather events. The solar storms associate with coronal mass ejections (CME), co-rotating interaction regions (CIR), and coronal holes, which, besides enhanced EM emissions, emit a high-energy stream of particles that can travel much faster than normal solar wind (Stix 2002).

Solar wind

Conceptual map code: 9, 14

A stream of charged particles, mostly electrons, protons, and alpha particles, coming from the upper atmosphere of the sun (the solar corona) and blowing through interplanetary space, typically at ~ 400 km^{-1} (Hargreaves 1992, Hundhausen 1995).

Solubility

Conceptual map code: 1, 8

The ability of a material to release ions in water or another liquid. Solubility may be expressed by the dissolution rate of the material and may also be described using words such as insoluble, very soluble, or poorly soluble (WHO, 2017).

Space weather

Conceptual map code: 9

The term space weather refers to highly disturbed conditions on the sun that lead to highly energetic particle and mass releases that impact on the Earth's magnetosphere, ionosphere, and thermosphere, causing storm-like disturbances and influencing the operation performance and reliability of space-borne and ground-based technological systems. Severe space weather conditions can also endanger human health (NASA 2020).

Sporadic E layer

Conceptual map code: 14, 16

Sporadic E are thin layers of enhanced ionization that exist mostly between about 95 and 125 km, with the strongest been observed at midlatitudes. They can at times become much denser than the normal E layer or even the peak F layer; thus, they may affect HF radio propagation and F region ionosonde recordings. The sporadic E layers (Es) form in the dynamo region (E region) of the ionosphere when metallic ions of meteoric origin are converged vertically in a wind shear by the action of geomagnetic and collisional forces. The physics of sporadic E layer formation is based on the *Windshear Theory*, first proposed and formulated in

the sixties by David Whitehead and Ian Axford. Today we know that the vertical wind shears needed for the layers to form are provided by atmospheric tides, mainly the semidiurnal tides. The occurrence and strength of sporadic E follow a pronounced seasonal dependence marked by a conspicuous summer maximum, which is likely due to the annual variation of sporadic meteor deposition in the upper atmosphere. Recently sporadic E is studied with satellite radio occultation (RO) methods of lower Earth orbiting (LEO) satellite GPS signals. Global RO observations confirmed key theory predictions, e.g., the role on Es formation of the horizontal component of the Earth's magnetic field. For details on sporadic E, see review papers by Whitehead (1989), Mathews (1998), and Haldoupis (2012).

Sprite halo

Conceptual map code: 2, 12, 13, 16

Sprite halo is an upper atmospheric optical phenomenon associated with thunderstorms. It is a diffuse flash of reddish light that precedes a sprite discharge, caused by the red line emissions of molecular nitrogen. A sprite halo is a diffuse disk surrounding the top of a sprite discharge, situated between at about 70 and 80 km and living only a few milliseconds. Contrary to elves, which are produced by lightning-released strong electromagnetic pulses (EMP), the sprite halo is a quasi-electrostatic (QE) field discharge phenomenon, as the sprite is, but without streamer development. Ionization and optical light emissions in the diffuse halo region and in the lower streamer region of sprites are observed to occur both as separate events and as closely coupled processes. The upper diffuse region of sprite halo, however, is characterized by fast relaxations of the QE driving fields because the conductivity at these upper heights is larger. Thus, sprite halos last much less than their fellow sprites with their ionization energies being too weak to cross the threshold required for streamer formation (Barrington-Leigh et al. 2001; Pasko et al. 2012).

St. Elmo's fire

Conceptual map code: 6, 7, 16

Corona or point discharges that occur when the environmental electric field is high, typically at the tips of sharp conductors (e.g., needles of coniferous trees, or ship masts) that enhance the electric field. This name was given to the phenomenon by Mediterranean sailors who regarded it as a visitation of their patron saint, Elmo (Erasmus). The appearance of St. Elmo's fire was regarded as a good omen, for it tends to occur in those latter phases of a violent thunderstorm when most of the surface wind and wave disturbance is over (Schonland 1950; MacGorman and Rust 1998).

Substorm

Conceptual map code: 13

The term substorm, or magnetospheric substorm, refers to abrupt and short-lived (1–2 h) geomagnetic field perturbations recorded by ground magnetometers in the high latitude auroral zones. They relate with intensified horizontal **E**x**B** Hall currents flowing in the E region ionosphere and strong magnetic field-aligned currents in the magnetosphere, and manifest the sudden release of energy into the ionosphere from the magnetotail where it has been accumulated. Substorms occur when the interplanetary magnetic field (IMF) turns southward which allows the penetration and coupling of solar wind energy with the Earth's magnetic field and the ionosphere. During substorms, a series of dynamic physical phenomena take place in the auroral zone, the most characteristic being the sudden appearance and intense brightening of rapidly moving auroral arcs. Substorms are more frequent and have much smaller temporal and spatial scales compared with geomagnetic-solar storms which are more intense, less frequent, and last several days affecting the entire magnetosphere and atmosphere. The complexity of the geomagnetic substorm phenomena has been a fascinating research field for many years (Lui 1992).

Sun-Earth connection

Conceptual map code: 20

Complex coupling processes relating solar variability with changes in the Earth and its geospace environment. The main part includes solar electromagnetic wave and energetic particle interactions with the Earth's atmosphere, and effects linking the magnetic fields of the sun, the solar wind, with the Earth's magnetic field, the ionosphere, and the neutral atmosphere, all relating to space weather and climate (Hargreaves 1992; Kivelson and Russel 1995).

Sunspot

Conceptual map code: 9, 14, 16

A temporary disturbed area in the solar photosphere that appears dark because it is cooler than the surroundings. There, the magnetic field flux is particularly strong which causes energetic particles to be trapped which reduces free vertical convection; therefore, part of the internal heat is prevented from reaching the surface. Typical sunspot sizes compare with the size of the Earth. They usually occur in pairs or in groups of opposite magnetic field polarity that move in unison across the face of the sun as it rotates. The sunspot number activity changes periodically with an average period of 11 years, known as the "11-year solar cycle". The highest point of sunspot occurrence during a cycle is known as solar maximum,

and the lowest sunspot occurrence point as solar minimum (Priest 1995).

Tectonic plates

Conceptual map code: 9, 14, 16

The tectonic plates are the large, thin, relatively rigid plates that move relative to one another on the outer surface of the Earth (USGS 2020).

Ternary homogeneous nucleation

Conceptual map code: 1

Ternary homogeneous nucleation (THN) is a heteromolecular nucleation process that involves three substances. It is used to explain new aerosol particle formation in the lower atmosphere. A typical system is the homogeneous nucleation of sulfuric acid (H_2SO_4), water (H_2O), and ammonia (NH_3) (Benson et al. 2010).

Terrestrial gamma flashes

Conceptual map code: 14

A burst of gamma rays produced in the Earth's atmosphere, typically lasting 0.2–3.5 ms, and having energies of up to 20 MeV (million electron volts). It is speculated that terrestrial gamma flashes (TGFs) are caused by intense electric fields produced inside thunderstorms in association with lightning leaders (Fishman et al. 1994; Smith et al. 2005).

Thoracic fraction

Conceptual map code: 1, 8

The mass fraction of inhaled particles penetrating beyond the larynx (ECS1, 1993).

Thundercloud

Conceptual map code: 12, 13

An electrified cloud, of cumulonimbus type, in which at least one lightning discharge is produced. A rain-bearing cloud that also produces lightning. The convective cell of a cumulonimbus cloud that generates lightning and thunder is a thunderstorm cell (Magono 1980; MacGorman and Rust 1998; Rakov and Uman 2002).

Thunderstorm ground enhancement

Conceptual map code: 12, 13

Enhanced fluxes of high-energy electrons, gamma rays, and neutrons associated with lightning discharges (Chilingarian et al. 2019).

Transient luminous event

Conceptual map code: 2, 12, 13, 16

The collective name for various optical phenomena which occur within the altitude range of 15–110 km as a consequence of the rapid redistribution of electric charge in an underlying active thunderstorm. These brief flashes with optical duration much less than a fraction of a second can occur in many forms and are believed to have different production mechanisms. TLEs in the mesosphere (sprites, sprite halos, and gigantic jets) can perturb the propagation of VLF waves propagating in the Earth-ionosphere waveguide while TLEs at high altitudes (sprites, gigantic jets, ELVES) perturb (i.e., heat or otherwise influence) the lower ionosphere, and can cause secondary effects on radio signals propagating in the Earth-ionosphere waveguide (Rodger 1999, Rakov and Uman 2002, Fullekrug et al. 2006, Pasko et al. 2012). See "red sprite" and "blue/gigantic jets".

Translocation

Conceptual map code: 1, 8

The transfer of material absorbed from the respiratory tract to other tissues in the body (ICRP 1994).

Triboelectrification/triboelectricity

Conceptual map code: 2, 3, 6, 7, 8

A process of charge separation that involves the rubbing together of material surfaces. The detailed physical mechanism in triboelectrification is a long unsolved problem. Triboelectrification in the atmosphere can result in fields produced inside dust clouds. Triboelectricity is static electricity generated during the contact or friction between the surfaces of dissimilar materials. When separated, each material acquires a charge of opposite polarity, hence undergoing triboelectric charging. It is a synonym of contact electrification. The triboelectric series is a classification scheme for the ordering of the tendency for positive charge acquisition in rubbing (Diaz and Felix-Navarro 2004).

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References

Adrovic F (2012) Editor, Gamma radiation, IntechOpen.

Alberts B (2014). Molecular biology of the cell (6th ed.). New York. ISBN 9780815344322

Ambus Per, (2015) Sophie Zechmeister-Boltenstern Sophie, in Biology of the Nitrogen Cycle, 2007.G.P. Robertson1, P.M. Groffman2, in Soil Microbiology, Ecology and Biochemistry (4th Edition)

Apollonio F, Liberti M, Paffi A, Merla C, Marracino P, Denzi A, Marino C, d'Inzeo G (2013) Feasibility for microwaves energy to affect biological systems via nonthermal mechanisms: a systematic approach. IEEE Trans Microwave Theory Techn 61(5):2031–2045. https://doi.org/10.1109/TMTT.2013.2250298

Arnold F (1986) Atmospheric ions. Stud Environ Sci 26(103-133):135–142

Barrington-Leigh CP, Inan US, Stanley M (2001) Identification of sprites and elves with intensified video and broadband array photometry. J Geophys Res 106(2):1741

Bazilevskaya G (2000) Observations of variability in cosmic rays. Space Sci Rev 94:25–38. https://doi.org/10.1023/A:1026721912992

Benson D, Markovich A, Lee SH (2010) Ternary homogeneous nucleation of H2SO, NH3, H2O under conditions relevant to the lower troposphere. Atmos Chem Phys 10(9):22395–22414

Bonnafous P et al (1999) The generation of reactive-oxygen species associated with long-lasting pulse-induced electropermeabilization of mammalian cells is based on a non-destructive alteration of the plasma membrane. Biochim et BiophysActa (BBA) - Biomembr 1461:123–134. https://doi.org/10.1016/S0005-2736(99)00154-6

Bór (2013) Optically perceptible characteristics of sprites observed in Central Europe in 2007-2009. J Atmos Sol Terr Phys 92:151–177. https://doi.org/10.1016/j.jastp.2012.10.008

Bowker GE, Crenshaw HC (2007) Electrostatic forces in wind-pollination, Part 1: Measurement of the electrostatic charge on pollen. Atmos Environ 41(8):1587–1595

Buonsanto MJ (1999) Ionospheric storms–a review. Space Sci Rev 88: 563–601

Chafai DE et al (2019) Reversible and irreversible modulation of tubulin self-assembly by intense nanosecond pulsed electric fields. Adv Mater 31:e1903636

Chalmers JA (1949) Atmospheric electricity, 1st edn. Pergamon Press, Oxford

Chilingarian A, Soghomonyan S, Khanikyanc Y, Pokhsraryan D (2019) On the origin of particle fluxes from thunderclouds. Astropart Phys 105:54–62

Cifra M, Pospíšil P (2014) Ultra-weak photon emission from biological samples: definition, mechanisms, properties, detection and applications. J Photochem Photobiol B Biol 139:2–10. https://doi.org/10.1016/j.jphotobiol.2014.02.009

Cifra M, Fields JZ, Farhadi A (2011) Electromagnetic cellular interactions. Prog Biophys Mol Biol 105(3):223–246. https://doi.org/10.1016/j.pbiomolbio.2010.07.003

Cifra M, Apollonio F, Liberti M et al (2020) Possible molecular and cellular mechanisms at the basis of atmospheric electromagnetic field bioeffects. Int J Biometeorol. https://doi.org/10.1007/s00484-020-01885-1

Clarke D, Whitney H, Sutton G, Robert D (2013) Detection and learning of floral electric fields by bumblebees. Science 340:66–69

Clarke D, Morley E, Robert D (2017) The bee, the flower, and the electric field: electric ecology and aerial electroreception. J Comp Physiol A *203*(9):737–748

Corbet SA, Beament J, Eisikowitch D (1982) Are electrostatic forces involved in pollen transfer? Plant Cell Environ *5*(2):125–129

Daintith and Gould (2006) The facts on file dictionary of astronomy/ edited by John Daintith, William Gould New York, NY: Facts on File, c1994. Call # 520.3 FA. "Cosmic rays are a global source of ionization distributed through the Galaxy." Source: Dalgarno, A. (2006), Interstel

Dal Maso M, Kulmala M, Lehtinen KEJ, Mäkelä JM, Aalto P, O'Dowd CD (2002) Condensation and coagulation sinks and formation of nucleation mode particles in coastal and boreal forest boundary layers. J Geophys Res 107. https://doi.org/10.1029/2001jd00

Dal Maso M, Kulmala M, Riipinen I, Wagner R, Hussein T, Aalto PP, Lehtinen KEJ (2005) Formation and growth of fresh atmospheric aerosols: eight years of aerosol size distribution data from SMEAR II, Hyytiälä, Finland. Boreal Environ Res 1:2005

Diaz AF, Felix-Navarro RM (2004) A semi-quantitative tribo-electric series for polymeric materials: the influence of chemical structure and properties. J Electrost 62(4):277–290. https://doi.org/10.1016/j.elstat.2004.05.005

Djafer D, Irbah A (2013) Estimation of atmospheric turbidity over Ghardaïa city. Atmos Res, Elsevier 128:76–84. https://doi.org/10.1016/j.atmosres.2013.03.009ff.ffhal-00801475f

Dusenbery DB (1992) Sensory ecology. W.H. Freeman, New York ISBN 0-7167-2333-6

EC-GPHSW (2013) European Commission. Guidance on the protection of the health and safety of workers from the potential risks related to nanomaterials at work-guidance for employers and health and safety practitioners. Brussels

Encyclopedia Britannica, (2019) https://www.britannica.com/ Accessed 1.10.2019

European Committee for Standardization (1993) CEN-EN 481-workplace atmospheres-size fraction definitions for measurement of airborne particles.

Fernandez de Arroyabe P, Lecha Estela L, Schimt F (2017) Digital divide, biometeorological data infrastructures and human vulnerability definition. Int J Biometeorol 2018:733–740. https://doi.org/10.1007/s00484-017-1398-x

Feynman R (1970) The Feynman lectures on physics Vol II Addison-Wesley Publishing Longman.

Finlay CC et al (2010) International Geomagnetic Reference Field: the eleventh generation. Geophys J Int 183(3):1216–1230

Fishman GJ, Bhat PN, Mallozzi R, Horack JM, Koshut T, Kouveliotou C, Pendleton GN, Meegan CA, Wilson RB, Paciesas WS, Goodman SJ, Christian HJ (1994) Discovery of intense gamma-ray flashes of atmospheric origin. Science 264(5163):1313–1316. https://doi.org/10.1126/science.264.5163.1313

Forbush SE (1937) On the effects in cosmic-ray intensity observed during the recent magnetic storm. Phys Rev 51(12):1108–1109. https://doi.org/10.1103/PhysRev.51.1108.3

Franz RC, Nemzek RJ, Winckler JR (1990) Television image of a large upward electrical discharge above a thunderstorm system. Science 249:48–51

Freeman S, Quilin K, Allison L (1965) Biological science 5th edition. (2013) Pearson Publishing.p.1059.

Fullekrug, M., and M. J. Rycroft (2006) The contribution of sprites to the global atmospheric electric circuit. Earth Planets Space 58(9):1193–1196

Fundamentals of Electronics (1965) Volume 1b — Basic Electricity - Alternating Current. Bureau of Naval Personnel. 1965. p. 197

GFCS. WMO-WHO Global Framework for Climate Services (GFCS) (2020) http://www.wmo.int/gfcs/about-gfcs, Accessed 1.10.2019

Gonzalez WD, Joselyn JA, Kamide Y, Kroehl HW, Rostoker G, Tsurutani BT, Vasyliunas VM (1994) What is a geomagnetic storm? J Geophys Res Space 99(A4):5771–5792. https://doi.org/10.1029/93JA02867

GSFT - Glossary for the Solar Flare Theory (n.d.) web site by Gordon Holman and Sarah Benedict. Responsible NASA Official: Gordon D. Holman, Heliophysics Science Division, NASA/Goddard Space Flight Center, Solar Physics Laboratory / Code 671, Gordon.D.Holman@nasa.gov

Gueymard C (1998) Turbidity determination from broadband irradiance measurements: a detailed multi-coefficient approach. J Appl Meteorol 37:414–435

Gunn R (1954) Diffusion charging of atmospheric droplets by ions, and the resulting combination coefficients. J Atmos Sci 11(5):339–347

Haldoupis C (2012) Midlatitude sporadic E. A typical paradigm of atmosphere-ionosphere coupling. Space Sci Rev 168:441–461

Handbook of Biological Effects of Electromagnetic Fields (third), (2007) Edited by Frank S. Barnes and Ben Greenebaum, 2007, CRC Press Taylor & Francis Group Boca Raton 33487-32742

Hargreaves JK (1992) The solar-terrestrial environment. Cambridge Atmospheric and Space Science Series. Cambridge University Press

Harrison RG (2000) Cloud formation and the possible significance of charge for atmospheric condensation and ice nuclei. Space Sci Rev 94(1):381–396

Harrison RG (2013) The Carnegie curve. Surv Geophys 34:209–232. https://doi.org/10.1007/s10712-012-9210-2

Harrison RG, Nicoll KA (2018) Fair weather criteria for atmospheric electricity measurements. J Atmos Sol Terr Phys 179:239–250

Harrison RG, Tammet H (2008) Ions in the terrestrial atmosphere and other solar system atmospheres. Space Sci Rev 137:107–118. https://doi.org/10.1007/s11214-008-9356-x

Hayakawa M, Hattori K, Ando Y (2004) Natural electromagnetic phenomena and electromagnetic theory: a review. IEEJ Trans Fundam Mater 124(2004):72–79

Hekstra DR et al (2016) Electric-field-stimulated protein mechanics. Nature 540.7633(2016):400

Hinds W C (1982, 1999) Aerosol technology: properties, behavior and measurement of airborne particles, 2nd edn. Wiley, New York.

Hirsikko A, Nieminen T, Gagné S, Lehtipalo K, Manninen HE, Ehn M, Hõrrak U, Kerminen VM, Laakso L, McMurry PH, Mirme A, Mirme S, Petäjä T, Tammet H, Vakkari V, Vana M, Kulmala M (2011) Atmospheric ions and nucleation: a review of observations. Atmos Chem Phys 11:767–798. https://doi.org/10.5194/acp-11-767-2011

Hodgkin AL, Huxley AF (1952) Aquantitative description of membrane current and its application to conduction and excitation in nerves. J Physiol 117(4):500–544 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1392413/

Hoppel WA (1969) Application of three-body recombination and attachment coefficients to tropospheric ions. Pure Appl Geophys 75:158–166

Hörrak U, Salm J, Tammet H (2000) Statistical characterization of air ion mobility spectra at Tahkuse Observatory: classification of air ions. J Geophys Res 105(D7):9291–9302

Hundhausen AJ (1995) The solar wind. In: Kivelson MG, Russell CT (eds) Introduction to space physics. Cambridge University Press, pp 91–198

Hunting, E.R., Matthews, J., de Arróyabe Hernáez, P.F., England, S.J., Kourtidis, K., Koh, K., Nicoll, K., Harrison, R.G., Manser, K., Price, C. and Dragovic, S., (2020). Challenges in coupling atmospheric electricity with biological systems. u, pp.1-14. https://doi.org/10.1007/s00484-020-01960-7

ICRP (1994) International Commission on Radiological Protection Human respiratory tract model for radiological protection, Annual 66.

Imyanitov IM (1957) Instruments and methods for the study of atmospheric electricity (in Russian), Gostekhizdat.

Imyanitov IM, Chubarina EV (1967) Electricity of free atmosphere, (Gidrometeoizdat, 1965) NASA/NSF Israel Program for Scientific Translations.

Israël H (1971) Atmospheric electricity, Vol. I, Fundamentals, conductivity, ions, Israel Program for Scientific Translations, Jerusalem

Israël H (1973) Atmospheric electricity, Vol. II, Fields, charges, currents, Israel Program for Scientific Translations, Jerusalem.

James MR, Wilson L, Lane SJ, Gilbert JS, Mather TA, Harrison RG, Martin RS (2008) Electrical charging of volcanic plumes, Space Sci. Rev. 137:399–418. https://doi.org/10.1007/s11214-008-9362-z

Järvinen A, Aitomaa M, Rostedt A, Keskinen J, Yli-Ojanperä J (2014) Calibration of the new electrical low pressure impactor (ELPI+). J Aerosol Sci 69:150–159. https://doi.org/10.1016/j.jaerosci.2013.12.006

Kathren, RL (1998) NORM sources and their origins. Applied Radiation and Isotopes, 49(3):149–168.

Kirkby J, Duplissy J, Sengupta K, Frege C, Gordon H, Williamson C, Heinritzi M, Simon M, Yan C, Almeida J, Tröstl J, Nieminen T, Ortega IK, Wagner R, Adamov A, Amorim A, Bernhammer AK, Bianchi F, Breitenlechner M, Brilke S, Chen X, Craven J, Dias A, Ehrhart S, Flagan RC, Franchin A, Fuchs C, Guida R, Hakala J, Hoyle CR, Jokinen T, Junninen H, Kangasluoma J, Kim J, Krapf M, Kürten A, Laaksonen A, Lehtipalo K, Makhmutov V, Mathot S, Molteni U, Onnela A, Peräkylä O, Piel F, Petäjä T, Praplan AP, Pringle K, Rap A, Richards NAD, Riipinen I, Rissanen MP, Rondo L, Sarnela N, Schobesberger S, Scott CE, Seinfeld JH, Sipilä M, Steiner G, Stozhkov Y, Stratmann F, Tomé A, Virtanen A, Vogel AL, Wagner AC, Wagner PE, Weingartner E, Wimmer D, Winkler PM, Ye P, Zhang X, Hansel A, Dommen J, Donahue NM, Worsnop DR, Baltensperger U, Kulmala M, Carslaw KS, Curtius J (2016) Ion-induced nucleation of pure biogenic particles. *Nature* 533:521–526. https://doi.org/10.1038/nature17953

Kivelson MG, Russel ZT (1995) Introduction to space physics. Cambridge University Press, Cambridge

Kulkarni P, Baron PA, Willeke K (2011) Aerosol measurement: principles, techniques, and applications, 3rd edn. Wiley, New York

Kulmala M, Petäjä T, Nieminen T, Sipilä M, Manninen HE, Lehtipalo K, Dal Maso M, Aalto PP, Junninen H, Paasonen P, Riipinen I, Lehtinen KE, Laaksonen A, Kerminen VM (2012) Measurement of the nucleation of atmospheric aerosol particles. Nat Protoc 7(9): 1651–1667. https://doi.org/10.1038/nprot.2012.091 https://www.nature.com/articles/nprot.2012.091

Kulmala M, Petaja T, Ehn M, Thornton J, Sipila M, Worsnop DR, Kerminen VM (2014) Chemistry of atmospheric nucleation: on the recent advances on precursor characterization and atmospheric cluster composition in connection with atmospheric new particle formation. Annu Rev Phys Chem 65:21–37

L'Annunziata MF (2016) Radioactivity, Elsevier

Laakso L, Anttila T, Lehtinen KEJ, Aalto PP, Kulmala M, Hõrrak U, Paatero J, Hanke M, Arnold F (2004) Kinetic nucleation and ions in boreal forest particle formation events. Atmos Chem Phys 4: 2353–2366. https://doi.org/10.5194/acp-4-2353-2004

Lee J-H, Jang A, Bhadri PR, Myers RR, Timmons W, Beyette FR, Papautsky I (2006) Fabrication of microelectrode arrays for in situ sensing of oxidation reduction potentials. Sensors Actuators B 115: 220–226.

Liberti M, Apollonio F, Merla C, D'Inzeo G (2009) Microdosimetry in the microwave range: a quantitative assessment at single cell level. IEEE Antennas Wireless Propagation Lett 8(5170009):865–868

Lidén G (2011) The European Commission tries to define nanomaterials. Ann OccupHyg 55:1–5. https://doi.org/10.1093/annhyg/meq092

Liu KN (2002) An introduction to atmospheric radiation. Academic Press, Cambridge

Love JJ, Bedrosian PA (2019) Extreme-event geoelectric hazard maps. In: Buzulukova N (ed) Extreme events in geospace-origins, predictability, and consequences. Elsevier, Amsterdam, pp 209–230

Lui ATY (1992) Magnetospheric substorms. Physics Fluids B: Plasma Physics 4:2257–2263. https://doi.org/10.1063/1.860194

Maccarrone M, Fantini C, Finazzi Agrò A, Rosato N (1998) Kinetics of ultraweak light emission from human erythroleukemia K562 cells upon electroporation. Biochim et BiophysActa (BBA) - Biomembr 1414:43–50. https://doi.org/10.1016/S0005-2736(98)00150-3

MacGorman D, Rust WD (1998) The electrical nature of storms. Oxford University Press, New York

Mach DM, Blakeslee RJ, Bateman MG (2011) Global electric circuit implications of combined aircraft storm electric current measurements and satellite-based diurnal lightning statistics. J Geophys Res 116:D05201. https://doi.org/10.1029/2010JD014462

Magono C (1980) Thunderstorms. Elsevier, Amsterdam

Markson R (2007) The global circuit intensity: its measurement and variation over the last 50 years. Bull Am Meteorol Soc 88(2):223–242. https://doi.org/10.1175/BAMS-88-2-223

Marracino P et al (2019) Tubulin response to intense nanosecond-scale electric field in molecular dynamics simulation. Sci Rep 9.1(2019): 10477

Mathews JD (1998) Sporadic E: current views and recent progress. J Atmos Sol-Terr Phys 60:413

McIver SB (1985) Mechanoreception. In: Kerkut GA, Gilbert LI (eds) Comprehensive Insect Physiol, Biochem and Pharma, 6th edn. Pergamon Press, Oxford

McPherron RL (1995) Magnetospheric dynamics. In: Kivelson MG, Russell CT (eds) Introduction to space physics. Cambridge University Press, Cambridge, pp 400–457

Mirabel PJ, Jaecker-Voirol A (1988) Binary homogeneous nucleation. In: Wagner PE, Vali G (eds) Atmospheric aerosols and nucleation. Lecture Notes in Physics, 309th edn. Springer, Berlin

Mirme A, Tamm E, Mordas G, Vana M, Uin J, Mirme S, Bernotas T, Laakso L, Hirsikko A, Kulmala M (2007) A wide-range multi-channel air ion spectrometer. Boreal Environ Res 12:247–264

Miroshnichenko L (2015) Solar cosmic rays: fundamentals and applications. Springer, Berlin

Mitsutake G, Otsuka K, Hayakawa M, Sekiguchi M, Corndlissen G, Halberg F (2005) Does Schumann resonance affect our blood pressure? Biomed Pharmacother 59:S10–S14

Munn RE (1987) Bioclimatology. In: Climatology. Encyclopedia of Earth Science. Springer, Boston. https://doi.org/10.1007/0-387-30749-4_26

NASA (2020) https://www.nasa.gov/mission_pages/rbsp/science/rbsp-spaceweather.html Accessed in February 2020

Neubert T, Rycroft M, Farges T, Blanc E, Chanrion O, Arnone E, Odzimek A, Arnold N, Enell C-F, Turunen E, Bosinger T, Mika A, Haldoupis C, Steiner RJ, Van der Velde O, Soula S, Berg P, Boberg F, Thejll P, Christiansen B, Ignaccolo M, Fullekrug M, Verronen PT, Montanya J, Crosby N (2008) Recent results from studies of electric discharges in the mesosphere. Surv Geophys 29: 71–137. https://doi.org/10.1007/s10712-008-9043-1

Nickolaenko AP, Hayakawa M, Hobara Y, (2010) Q-Bursts: natural ELF radio transients, Surv Geophys, Volume 31 4:409-425. https://doi.org/10.1007/s10712010-9096-9

Nickolaenko AP, Hayakawa M (2002) Resonances in the Earth–ionosphere cavity. Kluwer Academic Publishers, Dordrecht

Odzimek A, Baranski P, Kubicki M, Jasinkiewicz D (2018) Electrical signatures of nimbostratus and stratus clouds in ground-level vertical atmospheric electric field and current density at mid-latitude station Swider, Poland. Atmos Res 109C:188–203. https://doi.org/10.1016/j.atmosres.2018.03.018

Ogawa T, Tanaka Y, Yasuhara M, Fraser-Smith AC, Gendrin R (1967) Worldwide simultaneity of occurrence of a Q-type burst in the Schumann resonance frequency range. J Geomagn Geoelectr 19: 377–384

Ouzounov D, Pulinets S, Hattori K, Taylor P (2018) Pre-earthquake processes: a multidisciplinary approach to earthquake prediction studies. American Geophysical Union, Washington

Palmer SJ, Rycroft MJ, Cermak M (2006) Solar and geomagnetic activity, extremely low frequency magnetic and electric fields and human health at the Earth's surface. Surv Geophys 27:557–595

Parkinson WL, Torreson OW (1931) The diurnal variation of the electric potential of the atmosphere over the oceans. Union Géodésique et Géophysique Internationale Bulletin 8:340–345

Pasko VP, Yair Y, Kuo C-L (2012) Lightning related transient luminous events at high altitude in the Earth's atmosphere: phenomenology, mechanisms, and effects, Space Sci. Rev. 168:475–516. https://doi.org/10.1007/s11214-011-9813-9

Pöschl U (2005) Atmospheric aerosols: composition, transformation, climate and health effects. Angewandte Chemie International Edition 44, no. 46 (2005): 7520–40.

Price C (2016) ELF Electromagnetic waves from lightning: the Schumann resonances. Atmosphere 7(9):116. https://doi.org/10.3390/atmos7090116

Price C, Williams E, Elhalel G, & Sentman D (2020). Natural ELF fields in the atmosphere and in living organisms. In J Biometeorol 1-8.

Priest ER (1995) Sun and its magnetohydrodynamics. In: Kivelson MG, Russell CT (eds) Introduction to space physics. Cambridge University Press, Cambridge, pp 58–90

Probstein RF, Hicks R (1993) Removal of contaminants from soils by electric fields. Science 260(5107):498–503

Purcell and Morin (2013) Harvard University. Electricity and Magnetism, 820 pages (3rd). Cambridge University Press, New York. ISBN 978-1-107-01402-2.

Rakov VA, Uman MA (2002) Lightning: physics and effects. Press, Cambridge University

Reiter R (1985) Fields, currents and aerosols in the lower atmosphere, Steinkopff Verlag, NSF Translation TT 76-52030

Repacholi, Michael HB, Greenebaum B (1999) Interaction of static and extremely low frequency electric and magnetic fields with living systems: health effects and research needs. Bioelectromagnetics 20(3):133–160

Revil A, Naudet V, Nouzaret J, Pessel M (2003) Principles of electrography applied to self-potential electrokinetic sources and hydrogeological applications. Water Resour Res 39(5)

Rich PR (2003) The molecular machinery of Keilin's respiratory chain. Biochem Soc Trans 31(Pt 6):1095–1105. https://doi.org/10.1042/BST0311095

Rishbeth H, Garriot OK (1969), Introduction to ionospheric physics, Academic Press.

Rodger CJ (1999) Red sprites, upward lightning, and VLF perturbations. Rev Geophys 37(3):317–336. https://doi.org/10.1029/1999RG900006

Rogers RR (1979) A short course in cloud physics. Press, Pergamon

Ross E, Chaplin WJ (2019) The behaviour of galactic cosmic-ray intensity during solar activity cycle 24. Sol Phys 294:8

Ruggeri F, Zosel F, Mutter N, Różycka M, Wojtas M, Ożyhar A, Schuler B, Krishnan M (2017) Single-molecule electrometry. Nat Nanotechnol 12(5):488–495

Runge J, Balasis G, Daglis IA, Papadimitriou C, Donner RV (2018) Common solar wind drivers behind magnetic storm-magnetospheric substorm dependency. Nat Sci Rep 8:16987. https://doi.org/10.1038/s41598-018-35250-5

Rycroft MJ, Odzimek A (2010) Effects of lightning and sprites on the ionospheric potential, and threshold effects on sprite initiation, obtained using an analog model of the global atmospheric electric circuit. *J Geophys Res* 115:A00E37. https://doi.org/10.1029/2009JA014758

Rycroft MJ, Israelsson S, Price C (2000) The global atmospheric electric circuit, solar activity and climate change. J Atmos Sol-Terr Phys 62: 1563–1576. https://doi.org/10.1016/S1364-6826(00)00112-7

Schonland BFJ (1950) The flight of thunderbolts. 44–47.

Schumann, WO (1952) Z. Naturforsch. A, 7, 149-154, doi: https://doi.org/10.1515/zna-1952-0202.

Schwan HP (1999) Bioelectromagnetics, Carl Durney, and dosimetry: Some historical remarks. Bioelectromagnetics 20:3–8

Seinfeld JH, Pandis SN (2016) Atmospheric chemistry and physics: from air pollution to climate change, 3rd ed. John Wiley & Sons

Sentman DD (1995) Schumann resonances. In: Volland H (ed) Handbook of atmospheric electrodynamics, 1st edn. CRC Press, London, pp 267–296

Shibata K, Magara T (2011) Solar flares: magnetohydrodynamic processes. Living Rev Sol Phys 8:6. https://doi.org/10.12942/lrsp-2011-6

Shuman NS, Hunton DE, Viggiano AA (2015) Ambient and modified atmospheric ion chemistry: from top to bottom. Chem Rev 115: 4542–4570. https://doi.org/10.1021/cr5003479
Singh D, Gopalakrishnan V, Singh RP et al (2007) The atmospheric global electric circuit: an overview. Atmos Res 84:91–110
Smith DM, Lopez LI, Lin RP, Barrington-Leigh CP (2005) Terrestrial gamma-ray flashes observed up to 20 MeV. Science 307:1085–1088. https://doi.org/10.1126/science.1107466
Sollazzo A, Brzozowska B, Cheng L, Undholm L, Haghdoost S, Scherthan H, Wojcik A (2017) Alpha particles and X rays interact in inducing DNA damage in U2OS cells. Radiat Res 188:400–411
Sontag ES, Borgnakke C, Van Wylen GJ (2003) Fundamentals of thermodynamics, 6th Edition, John Wiley & Sons
Soula S et al (2011) Gigantic jets produced by an isolated tropical thunderstorm near Reunion Island. J Geophys Res 116(D19103):14. https://doi.org/10.1029/2010JD015581
Stix M (2002) The sun. An introduction, Springer.
Tandberg-Hansen E (2009) The physics of solar flares. Cambridge University Press, Cambridge
Tsong TY, Astumian RD (1986) 863—absorption and con-version of electric field energy by membrane bound ATPases. Bioelectrochem Bioenergetics 15, no 3(1986):457–476
Uman M (2008) The art and science of lightning protection, Cambridge University Press, Cambridge
UNSCEAR (2016) United Nations Scientific Committee on the Effects of Atomic Radiation. UNSCEAR Report, Report to the General Assembly, Annex B.
USGS (2020) Geological Survey Earthquake Hazards Program https://earthquake.usgs.gov/. (Accessed in 2020)
Vallero DA (2014) Fundamentals of air pollution, Academic Press
Volland H (1984) Atmospheric electrodynamics, physics and chemistry in space, Springer- Verlag.
Volland H (1995) Handbook of Atmospheric Electrodynamics. Editor CRC Press Revivals, 2017
Vorenhout M, van der Geest HG, van Marum D, Wattel K, Eijsackers HJP (2004) Automated and continuous redox potential measurements in soil. J Environ Qual 33(4):1562–1567. https://doi.org/10.2134/jeq2004.1562
Vorenhout M, van der Geest HG, Hunting ER (2011) An improved datalogger and novel probes for continuous redox measurements in wetlands. Int J Environ Anal Chem 91(7-8):801–810
Wahlin L (1986) Atmospheric electrostatics, Research Studies Press.
Wallace JM and Hobbs PV (2006) Atmospheric Science: an Introductory Survey, Elsevier
Wever R (1973) Human circadian rhythms under the influence of weak electric fields and the different aspects of these studies. Int J Biometeorol 17(3):227–232
White D (1999) The physiology and biochemistry of prokaryotes (2nd ed.). Oxford University Press.ISBN 978-0-19-512579-5.
Whitehead JD (1989) Recent work on midlatitude and equatorial sporadic E. J Atmos Sol-Terr Phys 51:401
Wiedensohler A (1988) An approximation of the bipolar charge distribution for particles in the submicron size range. J Aerosol Sci 19:387–389
Wiedensohler A, Birmili W, Nowak A, Sonntag A, Weinhold K, Merkel M, Wehner B, Tuch T, Pfeifer S, Fiebig M, Fjäraa AM, Asmi E, Sellegri K, Depuy R, Venzac H, Villani P, Laj P, Aalto P, Ogren JA, Swietlicki E, Williams P, Roldin P, Quincey P, Hüglin C, Fierz-Schmidhauser R, Gysel M, Weingartner E, Riccobono F, Santos S, Grüning C, Faloon K, Beddows D, Harrison R, Monahan C, Jennings SG, O'Dowd CD, Marinoni A, Horn HG, Keck L, Jiang J, Scheckman J, McMurry PH, Deng Z, Zhao CS, Moerman M, Henzing B, de Leeuw G, Löschau G, Bastian S (2012) Mobility particle size spectrometers: harmonization of technical standards and data structure to facilitate high quality long-term observations of atmospheric particle number size distributions. Atmos Meas Tech 5:657–685. https://doi.org/10.5194/amt-5-657-2012
Williams E, Mareev E (2014) Recent progress on the global electrical circuit. Atmos Res 135-136:208–227. https://doi.org/10.1016/j.atmosres.2013.05.015
Wilson CTR (1906) On the measurements of the earth-air current and on the origin of atmospheric electricity. Proc Camb Philol Soc 13:363–382
Wilson CTR (1921) Investigation on lightning discharges and on the electric field of thunderstorms. Philos Trans R Soc London Series A 211:73–115
Winzor DJ (2005) Protein charge determination. Curr Protocols Protein Sci 41(1):2–10
WMO (2017) International cloud atlas, manual on the observation of clouds and other meteors, WMO-No. 407 WMO, Geneva. https://cloudatlas.wmo.int/clouds-genera-cumulonimbus.html

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