# The Earth’s Electrical Surface Potential
## A summary of present understanding
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An explanation of the forces that drive the
electrical activity on the earth’s surface.
A basis for the concept of “earthing.”

## Contents

**Historical notes:** Additional information is provided throughout the document as "historical notes" for those interested in greater detail.

**Glossary:** Technical terms are explained in an expansive glossary found on pages 41-97.

## I. Introduction

For billions of years life has evolved on the earth. Only recently has man begun to wear shoes; and even more recently has man developed rubber and plastics (insulating materials) that are used to make shoes which insulate man completely from the earth. Today, a large portion of the population lives or works in high rise buildings. These circumstances put even more distance between man and the surface of the earth.

There is mounting evidence that the lack of contact with the earth's surface is detrimental to man's health. Recent research shows that connecting the human body to the earth's surface during sleep normalizes circadian cortisol profiles and reduces or eliminates stress-related symptoms, including sleep dysfunction, pain, digestive distress and anxiety[1]. Restoring the earth-connection also has a profound influence on inflammatory conditions. Studies verify that inflammation decreases and often disappears[2]. Brain waves, muscle tension, and blood volume pulse also normalize[3] when an individual is connected with the electrical surface potential of the earth.

Why is earthing beneficial to health? To answer this question an understanding of the electrical nature of the earth's surface is important. Herein we present the current understanding of earth's electrical potential, including an explanation of how it is generated and the fluctuations it is subject to.

## II. The Global Electrical Circuit

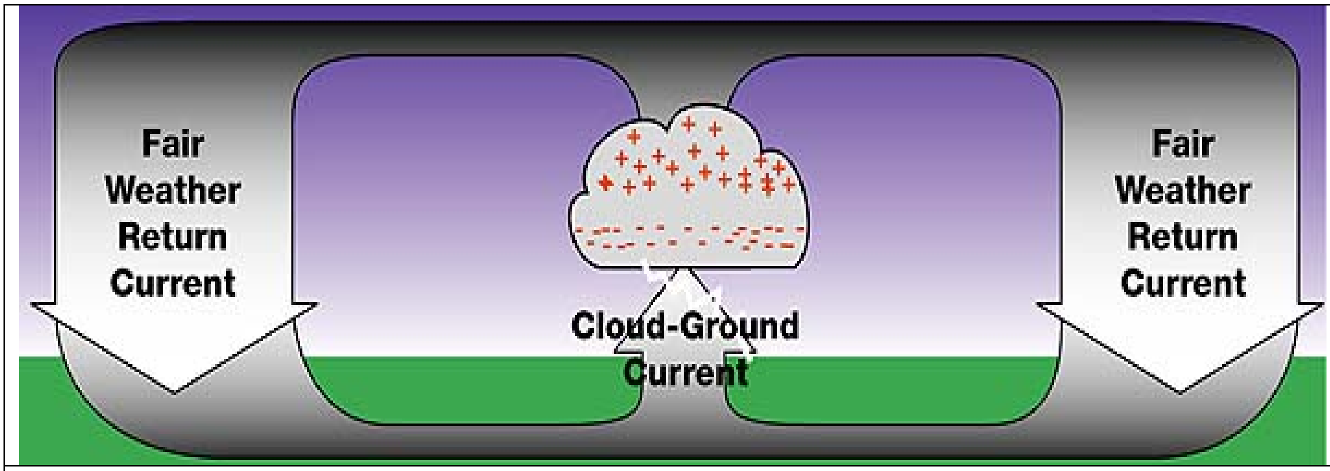
The earth's surface (oceans and land mass), are both highly conductive. Even the atmosphere conducts electricity because of the presence of positive and negative ions in the air.

The earth's electric current is the accumulated effect of thousands of thunderstorms, mostly in the tropical regions. These storms feed a continuous current from the ground to the ionosphere (a layer in the atmosphere that lies above 100 km (62.5 miles) altitude). The current spreads out around the globe via this layer and returns to earth as the "fair weather current" outside the thunderstorm areas[5]. The whole circuit is referred to as the "global electrical circuit."

For the most part, thunderstorms are created by cumulonimbus (Cb) clouds. The average cloud generates a current of about one amp (A) during its active period. With an estimated 1000 to 2000 thunderstorms continually active around the globe emitting close to 5000 lightning strikes per minute, there is an electric current of 1000 to 2000A continually transferring a negative charge to the surface of the earth. An equal and opposite charge remains in the upper atmosphere. The electrical charge continually flowing into the ionosphere maintains the fair weather current flowing to the surface[4].

**Properties of the global electrical circuit**

The current in the global electrical circuit is only about $10^{-12}$ amps (A) per square meter - almost nothing[5]. During fair weather there is an electric potential difference of 250,000 to 500,000 volts between the ionosphere and the earth's surface; the surface is negative relative to the ionosphere. It is estimated that this current (and the electric potential difference) would disappear in less than an hour if all thunderstorm activity ceased[13].



**Above**: Diagram shows fair weather circuit, also called "global electrical circuit", showing normal potential between the ground and atmosphere. Credit: NASA/MSFC (Dooling)

Most people are unaware that the atmosphere carries a continuous electric current. Even during fair weather, there is a strong electrostatic field of about 100 volts per meter close to the ground. This electric potential increases by about 100 volts per meter from the ground up. Atmospheric conductivity is lowest at sea level because ions tend to become attached to larger aerosol particles that are common near the surface[4]. However, conductivity increases rapidly as we approach the ionosphere.

The same pair of concentric conductors (earth's surface and the ionosphere) make up the electromagnetic waveguide that contains the earth's Schumann resonances which have a frequency of about 7.8 Hz. Both aspects of the global circuit - the direct current (DC) version with its 250,000 - 500,000 volts ionospheric potential and the alternating current (AC) version with Schumann resonances, provide integrated estimates of global weather measurable at single locations on the earth's surface[6].

Table 1 below presents a summary of the major properties of the global electrical circuit.

**Table 1: Some Properties of the Global Electric Circuit[13]**

| | | |
|---|---|---|
| Number of Thunderstorms Acting at One Time | | 1000-2000 |
| Currents above Thunderstorms (A) | | |
| (a) | Range | 0.1 to 6 |
| (b) | Average | 0.5 to 1 |
| Global Current (A) | | 750-2,000 |
| Ionospheric Potential (kV) | | |
| (a) | Range | 150-600 |
| (b) | Mean | 280 |
| Columnar Resistance at Sea Level ($\Omega/m^2$) | | |
| (a) | Low latitude | $1.3 \times 10^{17}$ |
| (b) | High latitude | $3 \times 10^{17}$ |
| (c) | Tibet and Antarctic plateau | $2 \times 10^{16}$ |
| Total Resistance ($\Omega$) | | 230 |
| | (including resistance decrease by mountains) | 200 |
| Current Density ($A/m^2$) | | |
| (a) | Inhabited and industrialized areas | $1 \times 10^{-12}$ |
| (b) | Vegetated ground and deserts | $2.4 \times 10^{-12}$ |
| (c) | South Pole Station | $2.5 \times 10^{-12}$ |
| Potential Gradient (V/m) | | |
| (a) | Equator | 120 |
| (b) | 60° latitude | 155 |
| (c) | South Pole | 71 |
| (d) | Industrial areas | 300-400 |
| Average Charge Transfer over the Entire World | | |
| | ($C\ km^{-2} yr^{-1}$) | + 90 |
| Total Charge on the earth (C) | | 500,000 |
| Electrical Relaxation Times | | |
| (a) | 70 km (43.75 miles) | $10^{-4}$ sec |
| (b) | 18 km (11.25 miles) | 4 sec |
| (c) | 0.01 km (0.00625 miles) | 5-40 min |
| (d) | earth's surface | $10^{-5}$ sec |
| Electrical Conductivity (mho/m) | | |
| (a) | Sea level | $10^{-14}$ |
| (b) | Tropopause | $10^{-13}$ |
| (c) | Stratopause | $10^{-10}$ |
| (d) | Ionosphere | |
| (i) | Pedersen conductivity | $10^{-4}$-$10^{-5}$ |
| (ii) | Parallel conductivity | 10 |

A fundamental property of the global electrical circuit is the electrical relaxation time at various altitudes. This is defined as the time the electric current takes to adjust to 1/e = 36.8% (e = 2.718281828 – Neper's number) of its final value after an electric field is suddenly applied, assuming that the conductivity remains constant. At high altitudes, near 70 km (43.75 miles), the relaxation time is about $10^{-4}$ second, increasing with decreasing altitude to about 4 seconds near 10 km (6.25 miles) and to about 5 - 40 minutes near the earth's surface. The electrical relaxation time of the land surface is about $10^{-5}$ second (due to its high conductivity). The maximum value of about 40 minutes in the atmosphere near the earth's surface is the characteristic time that the global circuit would take to discharge if all thunderstorm activity suddenly ceased. Measurements have never shown a complete absence of a fair-weather electric field, thereby suggesting the continuous activity of thunderstorms and other generators that maintain the currents flowing in the global circuit[13].

## Generators of the global circuit

In addition to the global generator (thunderstorms) there exist local generators such as precipitation, convection currents (charges moved by other than electrical forces), and blowing snow or dust. The latter create their own local current circuits and electric fields superimposed on parts of the global circuit. Generators can be regarded as local generators if the resistance from the upper terminal of the generator to the ionosphere is much greater than the resistance from that point to the earth's surface along the shortest possible path and with the consequence that almost no current flows to the ionosphere from this generator[13].

The main generators operating within the earth's global atmospheric circuit are summarized in Table 2 below.

**Table 2: Generators in the Global Electric Circuit[13]**

THUNDERSTORMS – current output maintains a vertical potential difference of 300,000 V between ground and ionosphere. Current ~ $10^3$ A.

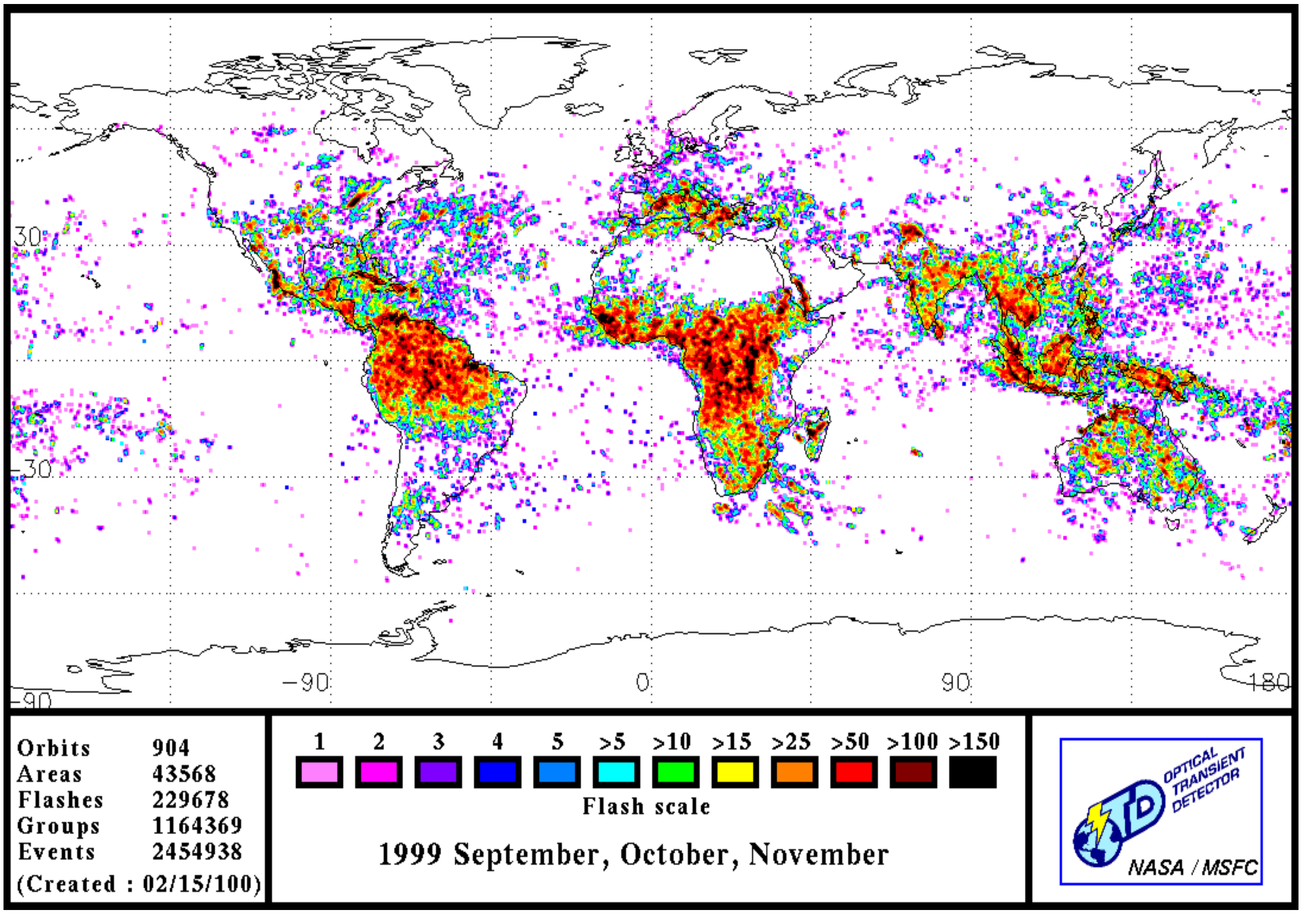
IONOSPHERIC DYNAMO – tides at ionospheric heights maintain horizontal potential differences of 5,000 - 15,000 V between high and low latitudes. Current ~ $10^5$ A.

MAGNETOSHERIC DYNAMO – interaction of solar wind with earth's geomagnetic field maintains a horizontal dawn-to-dusk potential drop of 40,000-100,000 V across polar caps. Current ~ $10^6$ A.

Thunderstorms are generators with a vertical potential difference of about 300 kV between the ground and ionosphere, and a total current flow of about $10^3$ A. The classical picture of atmospheric electricity assumes that the ionosphere is at a uniform potential, and that it does not account for either ionospheric or magnetospheric dynamos. The ionospheric dynamo is driven by both tides generated in situ and tides propagating upward from the lower atmosphere (see section on *Ionospheric Wind* and the glossary). These tides generate horizontal potential differences of 5 -10 kV within the ionosphere, with a total current flow on the order of $10^5$ A. The magnetospheric dynamo (see section on *Solar Wind – Magnetosphere* and the glossary), is driven by the interaction of the solar wind with the earth's geomagnetic field. It generates a horizontal dawn-to-dusk potential drop of typically 40 -100 kV across the magnetic polar cap and a total current flow of $10^6$ A. The magnetospheric convection pattern is Sun-aligned relative to the geomagnetic poles (north geomagnetic pole 78.3° N and 291° E, south geomagnetic pole 74.5° S and 127° E), and therefore the pattern remains fixed relative to the Sun but moves in a complex fashion over the earth's surface as the earth rotates about its geographic pole[13].

The biggest difficulty impeding progress in understanding the global circuit is the determination of the current output from thunderstorm generators. There are only a few measurements of the total current flow from storms, and there is a clear need for more measurements to define the current output properties in terms of thunderstorm size, duration, lightning flash frequency, charge separation distance, and other parameters[13].

In addition to single thunderstorm measurements, it is important to be able to obtain information on the global distribution of thunderstorm occurrence. Previous information has been derived from weather stations, from Schumann resonance, and from radio measurements. More recently, lightning detection from satellites has been used to derive information on the global distribution and flash-rate frequency from space[13] (see diagram on Thunderstorm Occurrence). Using that information researchers at NASA discovered that lightning not only likes land, it follows the Sun, and may even change its schedule to follow the El Niño/La Niña/Southern Oscillation phenomenon[9].



**Above**: Diagram showing thunderstorm activity over the world during September, October and November 1999. Note the heavy thunderstorm activity at equatorial locations.

## Basic model[13]

The atmospheric electric circuit is characterized by a difference in voltage on the order of 300 kV between the highly conductive ionosphere (commonly referred to as the equalization layer) and the earth's surface, which is also a good conductor. This voltage is thought to be maintained principally by thunderstorms acting as the generators and the atmospheric conductivity acting to discharge the ionosphere through continuous flow of current. The value of this air-earth current density $J_c$ in fair-weather areas depends on the ionospheric voltage $V_i$ and the columnar resistance $R_c$ and is, according to Ohm's law,

$$J_c = V_i / R_c.$$

The value of the atmospheric electric field E(h) at height h depends on the air-earth current and the electrical conductivity of the air at the same height according to Ohm's law relationship:

$$J_c = E(h)[\sigma_+(h) + \sigma_-(h)],$$

Where $\sigma_+(h)$ represents the electrical conductivity of positive ions and $\sigma_-(h)$ the electrical conductivity of negative ions. Under steady-state conditions it is expected that the air-earth current density is constant with altitude as long as large-scale horizontally homogeneous conditions exist and if no charged clouds or other disturbances alter the so-called fair-weather conditions. Typically the vertical electric field E(h) decreases exponentially with altitude during fair weather.

The good agreement with the mean columnar resistance value calculated from the conductivity and electric field profiles proved that the earth's surface and the ionosphere can be regarded as good conductors where charges are distributed worldwide within short times.

Direct measurements for the air-earth current density in the free atmosphere have been carried out with long-wire antenna sondes. Researchers reported a constant air-earth current throughout the troposphere and lower stratosphere.

At globally representative stations, the air-earth current density shows a diurnal variation vs. universal time with a minimum at around 0300 GMT (Greenwich Mean Time) and a maximum near 1800 GMT, reflecting the diurnal variations of the ionospheric potential. The agreement between these stations strongly supports the concept of a universally controlled global circuit.

**Historical Note**

Lightning was recognized as a grand manifestation of static electricity within thunderstorm clouds in the eighteenth century. It was also recognized that electrical phenomena are not confined to thunderclouds and that a weak electrification exists as a permanent property of the atmosphere even during fair weather. Further research established that the earth's surface is charged negatively and that the air is charged positively, with a vertical electric field of about 100 V/m existing in the atmosphere near the earth's surface. An electrostatic explanation for the phenomena was sought at first, and one theory suggested that the electric field of the atmosphere was the result of an intrinsic negative charge on the earth, probably collected during the earth's formation. With the discovery of cosmic-ray ionization in the early twentieth century, it was realized that air possesses an electrical conductivity due to its ion content. As a result of the finite electrical conductivity, vertical conduction currents flow from the atmosphere to the earth, tending to neutralize the charge on the earth. On the basis of actual conductivity values it was calculated that charge neutralization would take place in less than an hour, and the continued existence of an electric field suggested some generation mechanism to oppose the leakage currents flowing to the earth. The search for this generation mechanism soon became the main object of research on global atmospheric electricity.

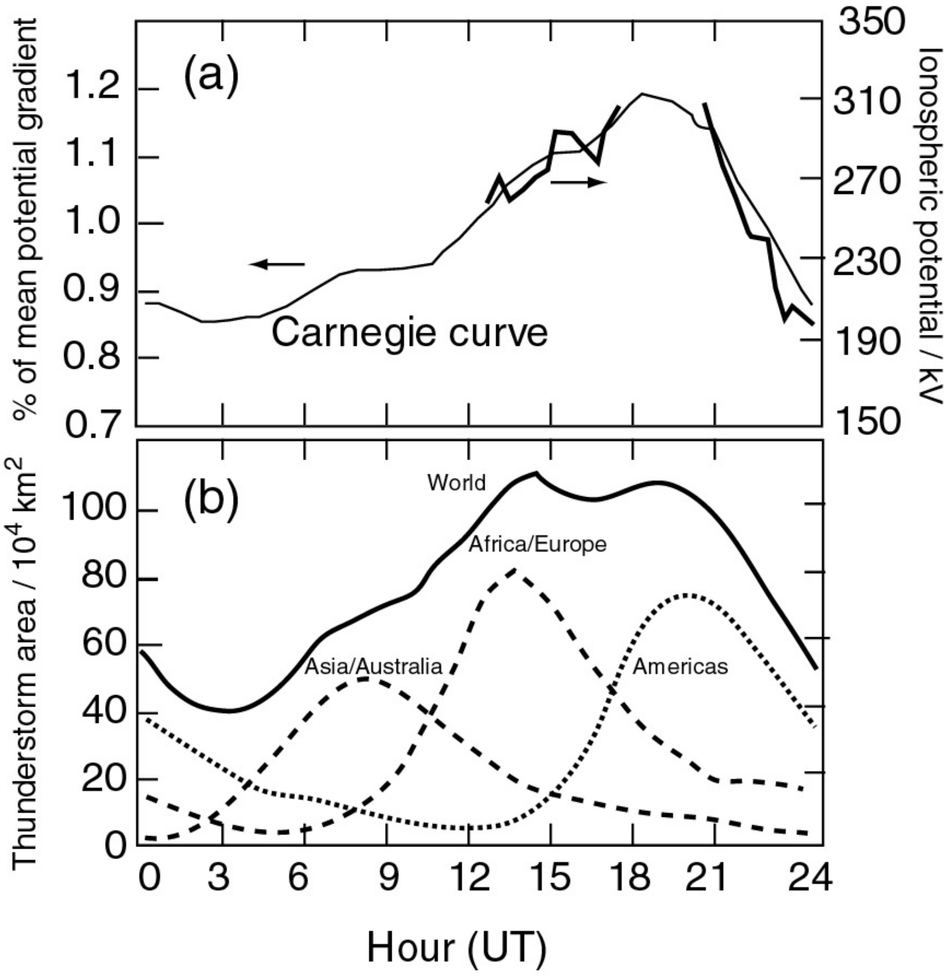
In the early twentieth century the concept of a global circuit of atmospheric electricity slowly began to evolve. The net positive space charge in the air between the ground and a height of about 10 km (6.25 miles) is nearly equal to the negative charge on the surface of the earth. The electrical conductivity of the air increases rapidly with altitude, and the product of the local vertical electric field and local conductivity at any altitude within an atmospheric column gives a constant air-earth current flowing downward. This constant air-earth current with respect to altitude implies that the current flow is mainly driven by a constant difference in potential between the surface of the earth and some higher altitude in the atmosphere. The discovery of the highly conducting ionosphere in the 1920s explained the long-range propagation of radio waves and was important for the evolution of the concept of the global electric circuit. The ionosphere, with its large electrical conductivity, provided a means of closing the global circuit. It, however, is not a perfect conductor parallel to the earth's surface, but it possesses a finite conductivity, and the electric currents and fields within it are driven by the combined action of the ionospheric and magnetospheric dynamo systems as well as by current generation from the lower atmosphere[13].

Wilson (1920) first demonstrated that a thunderstorm supplies a negative charge to the earth. In the 1920s, it was also known that over the oceans and in polar areas the diurnal maximum of the fair-weather potential gradient at the earth's surface occurred at the same Universal Time (about 1900 UT). Furthermore, radio measurements of atmospherics showed that global thunderstorm activity also peaked near 1900 UT, with the main thunderstorm centers being in Africa and South America (see diagram on thunderstorm activity). Scientists studying meteorological statistics of thunderstorm activity found similar diurnal variations. The diurnal UT variation of potential gradient over the oceans was similar to the diurnal UT variation of thunderstorm occurrence frequency with no phase delay. These experimental facts all contributed to the concept of the earth's global electrical circuit and furthermore suggested that thunderstorms were the generators within the circuit.

The thunderstorm generator hypothesis proposed by Wilson (1920) was based on his observations that beneath the thundercloud, negative charge is transferred to the earth; above the thundercloud, positive charge is transferred to the conductive upper atmosphere. A subsequent discovery was the close correlation between the diurnal UT variation of the thunderstorm generator current (represented by the frequency of thunderstorm occurrence) and the load current (represented by the fair-weather ground electric field or air-earth current density), integrated over the surface of the earth.

In about the 1920s the electric field over the oceans was found to vary diurnally in accordance with Universal Time (Parkinson and Torrenson, 1931), as shown in the upper frame of the figure below[13].

The similarity of the diurnal variation of electric field over the ocean and the diurnal variation of worldwide thunderstorm activity supports the hypothesis that thunderstorms are the electrical generator in the global circuit.



Above: (a) Annual curve of the diurnal variation of the atmospheric field on the oceans (volts per meter) as measured by the Carnegie expedition (Parkinson and Torrenson, 1931) and (b) annual curve of the diurnal variation of global thunderstorm activity according to Whipple and Scrase (1936)[13].

Although the similarity between the diurnal UT worldwide thunderstorm frequency curve and the diurnal UT electric-field curve suggests that thunderstorms are the generators in the global circuit, there is still considerable uncertainty concerning the details. Moreover, the data on which the thunderstorm activity is based are only of a qualitative nature: “a thunderstorm day is a day when thunder has been heard.” The commonly quoted UT diurnal patterns are averages over a long time and were made to reduce the influence of various disturbing factors. When shorter time averages are used – and even single diurnal variations – the correlations show great departures from the average curves. The variability of thunderstorm frequency can be large, with significant departures from the average; for example, whole continents may be cloudless for a long time. The measured electric field on the ground is also highly variable as a result of local influences, and it generally takes a week’s worth of averaging or more to bring out the diurnal UT pattern. Most measurements are made on continents, where the electric field displays variations with local time, and these measurements do not fit into a daily worldwide pattern but must be averaged to determine worldwide characteristics.

Orville and Spencer (1979) examined lightning flashes recorded in photographs by two satellites in the Defense Meteorological Satellite Program and found that most of the lightning is confined to land areas (now confirmed by more recent satellite pictures, see diagram) and that the ratio of global lightning frequency during northern summer to that of southern summer is about 1.4 for both the dusk and midnight satellite data. They pointed out that this summer-winter difference in global lightning frequency is opposite to the electric-field measurements. The hypothesized relation of the global atmospheric electric current to thunderstorms is still an unsettled question and needs to be resolved to make further progress in understanding the earth’s global atmospheric electric circuit.

## Historical Note References

Orville, R. E., and D.W. Spencer (1979). Global lightning flash frequency, *Mon. Weather Rev. 107*, 934-943.

Parkinson, W.C., and O. W. Torrenson (1931). The diurnal variation of the electric potential of the atmosphere over the oceans, Compt. Rend. de l’Assemblée de Stockholm, 1930; *IUGG* (sect. *Terrst. Magn. Electr. Bull. 8*, 340-345.

Whipple, F.J.W., and F. J. Scrase (1936). Point discharge in the electric field of the earth, *Geophys. Memoirs (London) VIII*(68), 20.

Wilson, C.R.T. (1920). Investigation on lightning discharges and on the electric field of thunderstorms, *Phil. Trans. A 221*, 73-115.

## III. Electrical Properties of the Earth's Surface

As previously mentioned, thunderstorms are generators whose current output maintains a vertical potential difference of about 300 kV between the ground and ionosphere, with a total current flow of about 1,000 A. Since the electrical conductivity of the earth's surface is large, horizontal electric fields can usually be neglected, and a vertical electric-field variation results to accommodate horizontal variations of ionospheric potential. Calculations have shown that the magnetospheric dynamo can produce perturbations of ± 20% in the air-earth current and ground electric field at high latitudes during quiet geomagnetic periods and larger variations during geomagnetic storms[13].

Because of its large electrical conductivity, the earth's surface can rapidly adjust to changes in electric potential (relaxation time $10^{-5}$ second, see Table 1). Variations of electric potential at different locations on the earth's surface result in currents called "telluric currents". Telluric currents consist of both the natural electric currents flowing within the earth (called earth currents), including the oceans, and the electric currents originating from man-made systems. Telluric currents could also be considered to include geodynamo currents, i.e., the electric currents that are presumed to flow in the earth's core and are responsible for the generation of the "permanent" geomagnetic field[13].

The fundamental causes of telluric currents are now believed to be understood. They are produced either through electromagnetic induction by the time-varying, external-origin geomagnetic field or whenever a conduction body (such as seawater) moves (because of tides or other reasons) across the earth's permanent magnetic field. Both causes produce telluric currents, which, in turn, produce magnetic fields of their own – fields that add to the geomagnetic field and produce a feedback on the ionosphere current system (a feedback that, however, is negligible)[13].

The complexities associated with telluric currents (and earth's surface electric potential variations) arise from the complexities in the external sources and in the conductivity structure of the earth itself. Such complexities have led earlier workers to make statements such as: "the simple laws of electromagnetic induction fully explain the cause of geoelectric and geomagnetic activity", while Winckler et al., (1959)[14], in discussing a 2,650-V drop across a transatlantic cable produced during a magnetic storm concluded, "…either the current circuit [in the Atlantic] is in the horizontal plane or the currents are not the result of the induced electromagnetic force (emf, see glossary)."[13]

The mathematical modeling of telluric currents, unlike the understanding of their physical causes, is still far from satisfactory. As far as earth currents are concerned, the investigations have been, for the most part, carried out on local or limited regional scale. In contrast, the understanding of oceanic telluric currents (which cover a considerable fraction of the earth's surface) has, since the Ashour (1950)[15] estimate of their decay time in an ocean (order of a few hours), undergone substantial progress. The state of the art of ocean-current modeling now takes into account coastlines, although the ocean bottom is usually assumed flat – either non-conducting (although with a conducting mantle) or conducting. Malin (1970, 1973)[16,17], in considering the lunar tidal harmonic component M2 (which is the most important one, both in the atmosphere and in the sea, with a period of half a lunar day), succeeded in separating the effect of direct electromagnetic induction from the ionosphere from the currents produced by oceanic tidal flow. He assumed that the geomagnetic variation associated with the tidal component should always be observed, independent of local time, whereas the ionosphere component should be negligible at midnight. In fact, he found that at Irkutsk (the geomagnetic observatory farthest from any ocean), the ocean-produced effect is negligible, unlike the situation at several other observatories closer to a coast, where the ocean component is present[13].

**Historical Note**

The first 75 to 100 years of earth current research produced considerable debate as to causes and magnitude of the effect at given times. Better agreement between independent measurements often occurred when relatively long lengths of wire were used. Today it is clear that such a situation could easily arise from experimental procedures: improper grounding of a wire or insufficiently high impedance in the measuring system. For example, in the work of Airy (1868), the wires were grounded to water pipes, which themselves could carry currents flowing in the entire region over which the relatively short lengths of wire extended. In this case, the pipe network was the receiving "antenna," even more than the lengths of wire. Recent evidence of the effect of telluric currents, integrated over a planetary scale, has been provided by analysis of MAGSAT data. Langel (1982) reported an analysis of the data in terms of separation, by spherical harmonic expansion, of the external- and internal-origin geomagnetic field. The analysis was done for different sets of data, depending on the value of the Dst index (a measure of the particle ring current in the earth's magnetosphere and, therefore, of the level of disturbance of the geomagnetic field). The internal term increases with decreasing Dst, unlike the external term, a consequence of the fact that induced currents must flow in the direction opposite to the inducing currents.

**Historical Note References:**

Airy, G. B. (1868). Comparison of magnetic disturbances recorded by self-registering magnetometers at the Royal Observatory, Greenwich, with magnetic disturbances described from the corresponding terrestrial galvanic currents recorded by the self-registering galvanometers of the Royal Observatory. *Phil. Trans. R. Soc. 158A*, 465-472.

Langel, R. A. (1982). Results from the MAGSAT mission, *Johns Hopkins APL Tech. Dig. 3*, 307-324.

### The natural environment[13]

Except during a lightning strike, essentially negligible electric current flows between the air and the ground (integrated over the earth, the fair-weather current amounts to some 1,000-2,000 A). Therefore, the earth's surface is a natural surface across which electromagnetic coupling occurs via electromagnetic field. This implies that it is possible, in many cases, to treat the coupling problem in terms of scalar potentials (at least for frequencies lower than those used in audio magnetotelluric studies; see glossary). The cause of telluric currents is either electromagnetic induction by the time-varying geomagnetic field produced by the ionosphere and/or magnetosphere or by water movement across the permanent geomagnetic field. Considering only the former case, the longer the period of the time-varying field, the greater the depth in the earth where the induced currents can be expected to flow. A quantitative criterion can be given in terms of electromagnetic induction in a half-space of uniform conductivity (note that this is a highly idealized case that practically never occurs in reality). The “skin depth” (i.e., the depth at which the external field is damped by a factor 1/e = 36.8%) is given by $S = 0.5(T/\ \ )^{0.5}$ km, where   is the conductivity in mhos/meter and T is the period of the variation in seconds. A signal with period of about 24 hours is generally believed to have a skin depth of 600 to 800 km (375 to 500 miles). (The skin-depth only provides a rough approximation of the depth at which actual telluric currents of a given period are flowing. In fact, the actual conductivity structure underground is most often a matter of considerable indeterminacy.) Saltwater has a conductivity of about 4 mhos/m, hydrated sediments have a conductivity of about 0.1 mho/m, and dry rock has a conductivity of about 0.0001 mho/m. Practically all the materials of usual geologic environment can be placed between these extremes. The conductivity of water is largely affected by salinity (and to a minor extent by temperature). The conductivity of soil is largely affected by the state of hydration. Porous materials and sediments can easily be hydrated by considerable amounts. Hence it might eventually be possible, by electromagnetic means, to distinguish materials of equal density but with different porosities, and hence different hydration (and electrical conductivities), that cannot be distinguished by seismic techniques.

The distribution of sediments, particularly important for shorter-period variations, should be considered on local or regional scales, because minor details in the distributions can be relevant to telluric current flow. Worldwide model maps of the total conductivity of the water shell plus sedimentary cover have been provided[13].

Another physical factor affecting conductivity, and thus telluric currents, is temperature. Since the temperature increases with depth in the earth, the conductivity is higher with increasing depth. However, the effect is not uniform; the heat flux through the earth’s surface is greater in certain regions than others, providing thermal anomalies. Whenever a large geothermal flux occurs, there is an upward warping of isothermal surfaces. In such a case, telluric currents of a given period will flow in shallower layers.

Three additional aspects of the conductivity structure of the earth affect the flow of telluric currents – spatial gradients, temporal variations, and channeling. The spatial gradients of telluric currents strongly depend, in shallow layers, on geochemical composition, geological structure, and hydration. [Hydration in this context can be taken just in terms of water content (producing an increase in conductivity) or in terms of the formation of particular compounds that can decrease the conductivity (although there are no reports of this in the telluric current literature).] Deeper in the earth, it is believed that a more or less thick layer of dry rocks (having reduced conductivity) is further underlain by layers of increasing conductivity, which is a function of the increasing temperature with depth. In such deep layers it has generally been assumed that the earth becomes increasingly homogeneous with greater depth. More realistically, however, the increasing difficulty (if not impossibility) of recognizing spatial gradients at greater depths must be acknowledged. Differently stated, telluric currents as a means of remote sensing of the underground conductivity provide ever-diminishing spatial (horizontal) resolution with depth.

The problem of spatial gradients of telluric currents is also related to the state of knowledge of the spatial gradients of the external-origin inducing field. In fact, the diurnal and the lunar variation fields (Sq and L fields, respectively) have a planetary scale, albeit showing strong spatial gradients related to the auroral and equatorial electrojets (large horizontal currents that flow in the ionosphere; see glossary) for quiet conditions. For disturbed conditions, the planetary-scale description still plays a relevant, though not singular, role. Therefore, the external-inducing source at these low frequencies can be approximately described in terms of a planetary-scale field, occasionally with strong spatial gradients. On the contrary, for higher frequencies (magnetic storms, geomagnetic pulsations) the source can often appear quite localized and is highly time dependent as well. At the earth's surface the spatial extent of the source for pulsations (period of a few to a few hundreds seconds) is believed to be not smaller than the height of the ionosphere.

Temporal variations in the earth's conductivity structure can be caused by such effects as seasonal climatic changes affecting water salinity and temperature, ice extension, permafrost and hydration content, and tectonic processes. The tectonic processes can be either slow (i.e., those involving the geologic time scale), intermediate (as in earthquake precursors), or rapid (as in volcanoes).

Effects on shallow telluric currents (generally shorter period) can be found whenever a mineral has some remarkably different electrical conductivity compared with that of the surrounding materials. This gives rise to a localized conductivity anomaly that can be studied by means of a dense network of recording instruments. Shallow currents have also been reported in several sedimentary basins, such as in the Seine Basin and in the northern German anomaly. Shallow telluric currents are responsible for a component of the coast effect or magnetic signals, where the geometrical orientations of the magnetic variations at higher frequencies are correlated with the shape of the coast.

The difference between shallow and deep effects (the latter arising from local tectonic features) has been shown by Honkura (1974)[18] for the Japanese islands. At shorter periods, when the skin depth is shallower, the coast effect reflects the coast shape. At longer periods, electromagnetic induction evidence suggests a dependence on the downward bending of the lithospheric slab where it approaches the Japanese subduction zone. Similar effects have been reported for a small island in the Philippine Sea ("regular' coast effect) and for the island of South Georgia (Scotia Arc, South Atlantic). The threshold period discriminating between shallow and deep effects appears to be about 20 minutes in the Japanese area.

### Interactions of telluric currents with man-made systems[13]

The natural telluric current environment can significantly affect man-made systems. Conversely, human technology can "pollute" the natural telluric current environment. The mechanisms by which these interactions occur, as well as their modeling, are far from being understood satisfactorily and comprehensively. Geophysicists have often viewed such interactions as an unwanted, unnatural nuisance. Engineers have almost always been concerned with thresholds of system reliability and with a system's capability to react positively to any sudden change in the natural environment, always on a strict basis of yield/cost ratio. Moreover, technological improvements have been progressively introduced within systems to ensure a higher and higher reliability, so that it becomes difficult to compare effects observed on different systems in different years.

**Communication cables**
Historically, this is the best investigated and documented effect of telluric currents on technological systems. In fact, after the lightning rod, the telegraph was essentially the earliest of man-made electromagnetic devices in use. Subsequently, telegraph lines have been progressively supplanted by telephone lines, and submarine cables have supplanted the former radio links between the telephone networks of different continents. Even with the advent of communication satellites, cable systems are still of major economic importance for long-distance communications.

The first detection of effects on a telegraph wire dates back to the years 1847-1852. The first observations appear to be from England by Barlow in 1849[19]. The days between August 28 and September 2, 1859, were also quite notable for some wonderful auroral displays and other phenomenon. Clement's (1860)[20] book had a self-explanatory title: *The Great Northern Light on the Night before 29 August 1859 and the Confusion of the Telegraph in North America and Europe*. According to Chapman and Bartels (1940)[21], this aurora was seen in the Atlantic at a latitude as low as 14° N, while in France 800 V were induced on a wire over a distance of 600 km. From Prescott (1866)[22]:

> *"We have, however, the second yet more wonderful effects of the aurora upon the wires; namely, the use of auroral current for transmitting and receiving telegraphic dispatches. This almost incredible feat was accomplished . . . on the wires of the American Telegraph Company between Boston and Portland, upon the wires of the Old Colony and Fall River Railroad Company between South Braintree and Fall River, and upon other lines in various parts of the country . . . Such was the state of the line on the September 2nd, 1859, when for more than one hour they held communication over the wires with the aid of celestial batteries alone."*

In 1910 work was begun in Norway by Carl Störmer of measuring the height of polar aurorae (Störmer, 1955[23]). Störmer used photographs taken simultaneously from two sites separated by less than a hundred kilometers. He was able to send a message of alert to his co-workers about an imminent night of photographic work whenever he measured disturbances in the local telegraph wires.

A geomagnetic storm in Sweden in May 1921 produced voltages of 6.3 to 20 V/km (i.e., 1 kV or more over 100 to 200 km, with 2.5 A, while the threshold for serious trouble was 15 mA). A large magnetic storm on April 16, 1938, produced potentials of several hundred volts over local wires in Norway. On March 24, 1940, a geomagnetic storm damaged the Norwegian wirelines (≤ 50-60 V/km, ~600V, >4 A), while in the United States, more than 500 V were estimated to have occurred along some lines. Reports from two sites near Tromso, Norway, stated:

> *". . . Sparks and permanent arcs were formed in the coupling racks and watch had to be kept during the night to prevent fire breaking out. . . . One line was connected to earth through a 2 mm thick copper wire, which at once got red hot, corresponding to a current more than 10 amps (Harang, 1951[24])."*

In the second half of the nineteenth century, earth currents in submarine cables were rather extensively investigated. Saunders (1880[25], 1881[26]) and Graves (1873) [27] reported some of their work, which included a cable between Suez and Aden and a cable between Valentia and Newfoundland. Wollaston (1881)[28] concluded that his current measurements on a submarine cable across the English Channel resulted from tidal currents and related in 1851 conversation with Faraday on the matter. The latter was quoted as quite enthused about this confirmation of his predictions.

Axe (1968) [29] listed several geomagnetic storm-induced effects on submarine cables occurring in 1957-1967 (total voltage drops from 50 V to 2,700 V for the different occurrences). The largest voltage drop occurred across a transatlantic cable (equivalent to 0.75 V/km) at the time of the huge storm on February 11, 1958, which produced a well-known spectacular auroral display down to low latitudes. It is noteworthy that "the cable to Hawaii which originates about 140 miles north of San Francisco exhibited no major voltage swings" (Winckler et al., 1959) [14].

A major geomagnetic event on August 4, 1972, caused the outage of a continental cable in the Midwestern United States. The outage has been investigated by modeling the telluric currents in terms of a compressed magnetosphere with magnetopause and magnetosphere currents electromagnetically inducing over a three-layer conducting earth.

Summarizing, shutdowns in both land and sea cables, as well as fires, have been caused by telluric currents induced by geomagnetic storms, and suitable precautions have to be taken in order to attempt to avoid them.

A singular example of man-made telluric current "pollution" occurred when a high-altitude nuclear bomb test produced perturbations in the earth's radiation belts and geomagnetic field. As recounted in Axe (1968) [29]:

> *"The disturbance was just detectable on the power-feeding voltage and current recorder charts on the Australia-New Zealand, United Kingdom-Sweden and Bournemouth-Jersey systems. On a circuit originally set up on the Donaghadee-Fort Kail No. 3 cable for the measurement of voltage due to water flow, the disturbance was clearly recorded."*

All the effects considered above refer to electromagnetic induction from ionospheric and magnetospheric variations. However, there are also effects on submarine communication cables related to water flows (tidal and otherwise). Less dramatic, although relevant, man-induced telluric current perturbations on land cables should be expected in heavily industrialized or populated areas.

### Powerlines

The historical record of powerlines being greatly distributed or completely disrupted by geomagnetic storms appears somewhat less detailed than that for communication cables. One interruption of service occurred on March 24, 1940, in New England, New York, Eastern Pennsylvania, Minnesota, Québec, and Ontario. As well, during the great geomagnetic storm of February 11, 1958, the Toronto area suffered from a blackout produced by a geomagnetic storm. Currents up to about 100 A were induced in some northern latitude transformers during the great storm of August 4, 1972.

The geomagnetic currents induced in a power system can produce problems of several different types. First, the arbitrary differential relay operation in power distribution systems during geomagnetic storms can produce a judgmental problem; system operators are unsure of whether the malfunctioning relay indication is an induced-current effect in a transformer or a real transformer malfunction. Second, the currents actually induced in the winding of a power transformer can result in half-cycle saturation of the transformer core. This saturation can produce fluctuations in the transformer operation itself. This local heating can greatly shorten the lifetime of a transformer.

The effects of induced telluric currents on power systems produce outages as well as damages to expensive transformers. It has been estimated that up to tens of amperes were produced on powerlines of 100 to 150 km (62.5 to 93.75 miles) length in Norilsk region (Siberia). Since 500-kV transformers capable of withstanding even 3 to 4 A without saturating appear to cause problems for manufacturing, a way of avoiding such serious damage is to use powerlines of limited total length (e.g., no more than 500 km (312.5 miles) for Alaska).

### Pipelines

Varley (1873)[30] reported that large earth currents on a short length of telegraph cable in London appear to have been related to currents flowing on large, nearby gas pipelines. Studies of induced telluric currents on pipelines took renewed importance when the long, trans-Alaskan pipeline [1,280 km (800 miles) long] was built. The effects of telluric currents appear to be of most importance in affecting electronic equipment related to operational monitoring and corrosion control rather than in producing specific serious corrosion problems.

Viewing a pipeline as man-made part of the natural environment, it is noteworthy to mention the 30-A current reported by Peabody (1979)[31] to cross the Panama Isthmus, from ocean to ocean, a current that also changes direction. Such specific currents can produce corrosion failures at some ocean terminals of the pipelines, even before the pipeline is in operation. Such problems can be avoided most simply by suitable separate ground connections.

The Alaskan pipeline has been the subject of careful investigations, principally because of its location across the auroral zone. Campbell and Zimmerman (1980)[32] provided a comprehensive account of the problem and concluded that the current $I$ expected to flow within the pipeline is related to the geomagnetic index $A_p$ by the linear relationship $I = 5.0 \times A_p - 0.7$. Based on the statistics of occurrences of the $A_p$ index (larger for greater geomagnetic activity), at least once a year about 600 A should be observed, 800 A should be observed at least once every 2 years, and 1,200 A should be observed at least once every 5 years. The dimensions of the Alaskan pipeline [diameter of ~1.22 m (48 inches), a mean wall thickness of ~1.30 cm (0.5 inch), a resistance per unit length of $\sim 2.81 \times 10^{-6}\ \Omega/\mathrm{m}$, and an end-to-end total resistance of 3.6 $\Omega$ (Campbell, 1979)[33]] suggest that it is a large man-made conductor that is capable of significantly affecting the local natural regime of telluric currents.

### Railways

Pollution by artificially produced telluric currents associated with railways operations have been investigated from several viewpoints. Burbank (1905) [34] reported the effects in 1890 of the South London Electric Railway on the earth current records being made at Greenwich. The nuisance for geomagnetic observations of telluric currents associated with return currents from DC electrified railways has perhaps been the most widely investigated effect. The spatial extent within the ground of telluric currents from railway operations has been investigated by Kovalevskiy et al. (1961)[35] in the southern Urals. They detected telluric current pulses with periods between a few seconds and 20 minutes and amplitudes of about 0.5 to 3 V/km. They found the effects to drop off rapidly within 10 to 15 km (6.25 to 9.4 miles) from the railway, although still being dominant over natural telluric currents at 30 km (18.75 miles), and still detectable at 60 km (37.5 miles) (where the measurements stopped). Meunier (1969)[36], following a previous investigation by Dupouy (1950)[37], detected telluric current effects related to a specific operation (lowering and raising the pantograph) of the Paris-Toulouse railway at 115 km (71.5 miles) distance from the railroad. This effect, in fact, can sometimes be detected on the magnetograms from the Chambon-la-Forêt observatory. Jones and Kelly (1966)[38] detected earth currents in Montreal, clearly correlated with a DC-powered railway some 20 km (12.5 miles) distant.

A most impressive telluric current effect in the San Francisco Bay area has been produced by BART (the San Francisco Bay Area Rapid Transit system). ULF waves (frequency less than 5 Hz) were observed, having energy at a frequency predominantly below about 0.3 Hz. Their amplitudes are at least ten times greater than the natural background environment, i.e., they are comparable with the levels reached during great geomagnetic storms. The effect originated by BART appears to occur over an area of about 100 km$^2$ (39 square miles).

A similar effect has been detected by Lowes (1982)[39] in Newcastle upon Tyne (U.K.) produced by the DC rapid transit underground railway system. Lowes also noted that when the system starts up in the morning he can follow individual train movements over about 12 km (7.5 miles) of track before there is too much superimposition of the signals.

### Corrosion

Corrosion in buried metal structures (in addition to pipelines) is significantly enhanced by the occurrence of telluric currents, presumably via electrolytic processes. This is a well-known phenomenon to people routinely working on repairs of telephone cables or of pipes (for water or otherwise). Severe damage comes mainly from man-made telluric currents when the conductors are buried close to DC-electrified railways or tramways. A simple insulating coating, provided that it has no holes, appears to be the best protection. The problem is discussed to some extent by Peabody (1979)[31]. The problem can exist also for buried powerlines that have, unlike aerial power lines, some relevant problems of heat flow.

### Biological Effects

The response of living species to electromagnetic fields (such fields being either responsible for, or a consequence of, telluric currents) is a difficult but important problem. Several examples discussed in the literature include the induced currents in a tree produced by geomagnetic fluctuations (Fraser-Smith, 1978)[40] and the use of magnetic fields for orientation by aquatic bacteria and by migrating birds. Telluric currents could play a role in some control of fish. Magnetite crystals have been reported as isolated from a sinus in the yellowfin tuna. Enhanced DNA synthesis has been reported for human fibroblasts exposed to magnetic-field fluctuations with frequencies and amplitudes similar to many geomagnetic occurrences (Liboff et al., 1984)[41]. The entire area is fraught with controversy, particularly that related to magnetic effects, and has been reviewed by Parkinson (1982)[42] and commented on by Thomson (1983)[43].

More recently, the advent of microwaves, radar and cellular telephones has spurred a large body of research – with conflicting results. An entire journal is now devoted to the question of the effects of EM fields on living systems (Bioelectromagnetics). The next few years will likely uncover much.

**Historical Note**

A selective sketch of the historical development of the understanding of telluric currents follows. It is impossible to give full justice to all authors.

1540 First reported measurements of geomagnetic declination and dip in London (as discussed, for example, in Malin and Bullard, 1981; Barraclough, 1982). For the early history of geomagnetism, including the works of Gilbert and Gauss, refer to Mitchell (1932a, 1932b, 1937), Chapman (1963), Mattis (1965, Chap. 1), Parkinson (1982, Chap. 6), and Merrill and McElbinny (1983).

1600 First modeling of the geomagnetic field by Gilbert's (1600) terrella (Malin, 1983).

1821 Davy (1821) suggested the existence of earth currents that, he argued, could be responsible for variations in the geomagnetic declination (Burbank, 1905).

1832 Faraday (1832) envisaged for the first time the existence of induced currents in water, related to water flows and tides. He also attempted, without success, to detect, from the Waterloo Bridge, such currents flowing within the Thames. Gauss (1833) reported the first measurements, on May 21, 1832, of the absolute value of the geomagnetic field (Malin, 1982).

1846 Barlow (1849) made the first observations, in England, "on the 1847 spontaneous electric currents observed in the wires of the electric telegraph."

1848 Matteucci detected induced currents in the telegraph wire between Florence and Pisa, while Highton observed the same effect in England.

1850 Similar effects were reported in the United States.

1859 A telegraph line in the United States was reported operated by means of the natural induced currents during geomagnetic disturbances on September 2.

1862 Lamont reported one of the first experiments to specifically address earth currents (carried out in the Munich Alps).

1865 Experiments by Airy (1868) on two wires of 13 and 16 km from Greenwich.

1867 Secchi reported measurements on two almost orthogonal telegraph lines of lengths 58 km [36.25 miles] (Rome-Arsoli) and 52 km [32.5 miles] (Rome-Anzio).

1881 The Electrical Congress, meeting in Paris, recommended that certain short lines be set apart in each country for the study of earth current phenomena and that longer lines be used as frequently as possible (Burbank, 1905).

1883 Blavier (1884) recorded, for 9 months, earth potentials on five long telegraph 1884 lines extending from Paris, ranging in length from 200 to 390 km (125 to 243.75 miles). See also Counil *et al.* (1983).

1884 Four complete years of records on two telegraph wires in Germany (262 1887 and 120 km [163.75 and 75 miles]) investigated by Weinstein (1902 and Steiner (1908).

1886 Shyda reported an earth current study on the land line plus ocean cable route from Nagasaki, Japan, to Fusan, Korea.

1889 Schuster (1883, 19080) performed the first investigation on the diurnal variation of the geomagnetic field. He concluded that the origin is external, that the earth must have an upper layer less conducting than that deep in the interior, and he proposed the “suggestive cause” of tidal motion in the atmosphere for the origin of the observed diurnal variation.

1892 Two orthogonal earth current lines ~ 15 km (9.4 miles) each, were established at Saint-Maur-des-Fossés Observatory southwest of Paris.(Moureaux, 1895, 1896; Bossler, 1912; Rougerie, 1940; Counil *et al*.1983).

1893 Moureaux found that the east-west earth currents in the Paris basin were “exactly” correlated with the H-component of the geomagnetic field (i.e., the horizontal, north-south component), while this did not appear to be true for the north-south earth current and the declination (east-west horizontal) geomagnetic field. This was the first reported detection of what is now interpreted in terms of telluric currents channeled east-west in the Seine basin from the Atlantic Ocean.

1905 Van Bemmelen (1908) found that geomagnetic storm sudden commencements (ssc’s) have opposite signs at Kew (close to London) and at St. Maur (close to Paris). He correctly explained this in terms of electric currents flowing in the English Channel.

1909 Schmidt investigated geomagnetic storms at Potsdam and at the Hilf Observatory (13 km [8.1 miles] south of Postdam).

1912 Van Bemmelen (1912, 1913) investigated the lunar period magnetic
1913 variation at 15 observatories.

1917 Terada (1917) and Dechévren (1918a, 1918b) investigated earth
currents 1918 in Japan and in England (Jersey), respectively.

1918 The British Admiralty succeeded for the first time to detect electromagnetic disturbances related to seawater flows (Young *et al*., 1920; figure reported in Chapman and Bartels, 1940).

1919 Chapman performed a systematic (and still quite valuable) analysis on the diurnal magnetic variation at 21 observatories, based on records collected in 1905.

1922 Bauer reviewed the status of earth current studies.

**Some historical points of interest in the past 80 years include:**

1923 Chapman and Whitehead (1923) appear to have been the first investigators to be concerned with induction effects associated with the auroral electrojet (a localized current system). They erroneously concluded that geomagnetic storm effects at low latitudes are produced by earth currents induced by the auroral electrojet.

1927 Baird (1927) and Skey (1928) detected for the first time (at Waterloo in 1928 Australia and at Amberley and Christchurch in New Zealand, respectively) the intersection of what is now called the Parkinson plane (see e.g., Gregori and Lanzerotti, 1980) with the DZ plane (i.e., the vertical, east-west oriented plane).
1930 Chapman and Price (1930) reconsidered the Chapman and Whitehead (1923) analysis and clearly stated that “the storm-time variations of the geomagnetic field in low latitudes cannot be due to currents, induced either in the earth or in a conducting layer of the atmosphere, by varying primary currents in the auroral zones.”

1931 Cooperative project between the U.S. Coast and Geodetic Survey, the Carnegie Institution of Washington, and the American Telephone and Telegraph Company initiated at Tucson magnetic observatory to study earth currents.

1936 Bossolasco detected for the first time (from measurements performed at Mogadiscio, Somalia, during the second International Polar Year, 1932-33) what is now called the Parkinson plane.

1949 De Wet attempted a numerical computation of the induction effects in oceans taking into account the coastal shapes.

1950 Ashour estimated the decay time of induced telluric currents within oceans. Constantinescu discovered what is now called the Parkinson plane and draw a plot, which is quite similar to a Wiese plot (see, e.g., Gregori and Lanzerotti, 1980).

1953 Rikitake and Yokoyama clearly stated the existence of the Parkinson plane. Banno detected for the first time the coast effect on earth currents at Memambetsu (Hokkaido).

1954 Fleischer (1954a, 1954b, 1954c) hypothesized an east-west electric conductor 70 to 100 km (43.75 to 62.5 miles) deep beneath Bremen. Kertz (1954) stated that it cannot be lower than 80 km (50 miles). Bartels (1957) estimated a depth of 50 to 100 km (31.25 to 62.5 miles). Schmucker (1959) estimated a cylinder 63 km (39.4 miles) in radius, 100 km deep. Porstendorter (1966) estimated high conductivity (0.2-0.5 mho/m) down to 10 km (6.25 miles) depth, an insulator (0.0001 mho/m) down to 100 km, a conductor (0.1 mho/m) between 100 and 130 km (62.5 and 81.25 miles), an insulator (0.0001 mho/m) between 130 and 400 km (81.25 and 250 miles), and 0.1 mho/m underneath. Vozoff and Swift (1968) reported a sedimentary layer (1.0 mho/m) 6 km (3.75 miles) deep in North Germany (8 sited from Braunschweig to Luebeck). The North German conductivity anomaly is now believed to be principally produced by surface-hydrated sedimentary layers that channel electric currents from the North Sea eastward to Poland. This is a classic example of how difficult the inversion (interpretation) problem is for geomagnetic measurements.

1955 Rikitake and Yokoyama appear to be the first authors to use the term “coast effect.” In theoretically calculating a model of electromagnetic induction in a hemispherical ocean, they noted an enhanced magnetic field close to coasts.

1958 Mansurov used the term “coastal effect” in analyzing geomagnetic measurements made at Mirny Station, Antartica.

1959 Parkinson 1959, 1962a, 1962b, 1964), in a series of classic papers, analyzed in detail what is now called the Parkinson plane for geomagnetic measurements.

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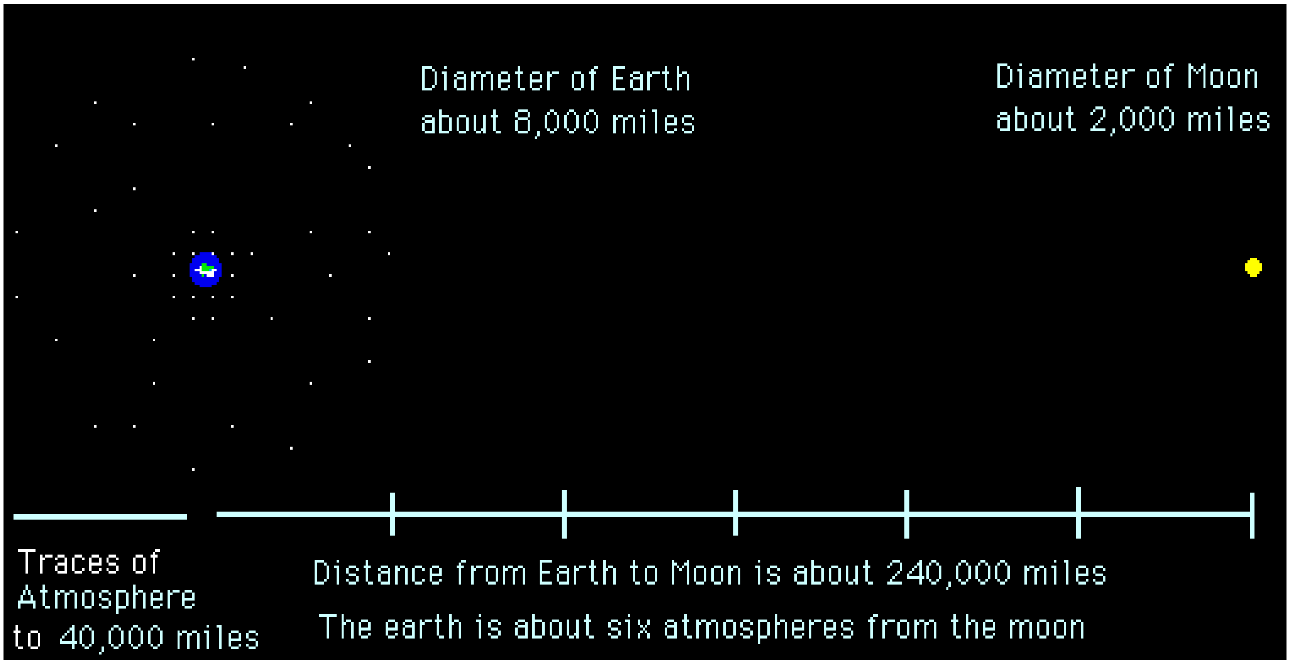
## IV. Electrical Properties of the Earth's Atmosphere

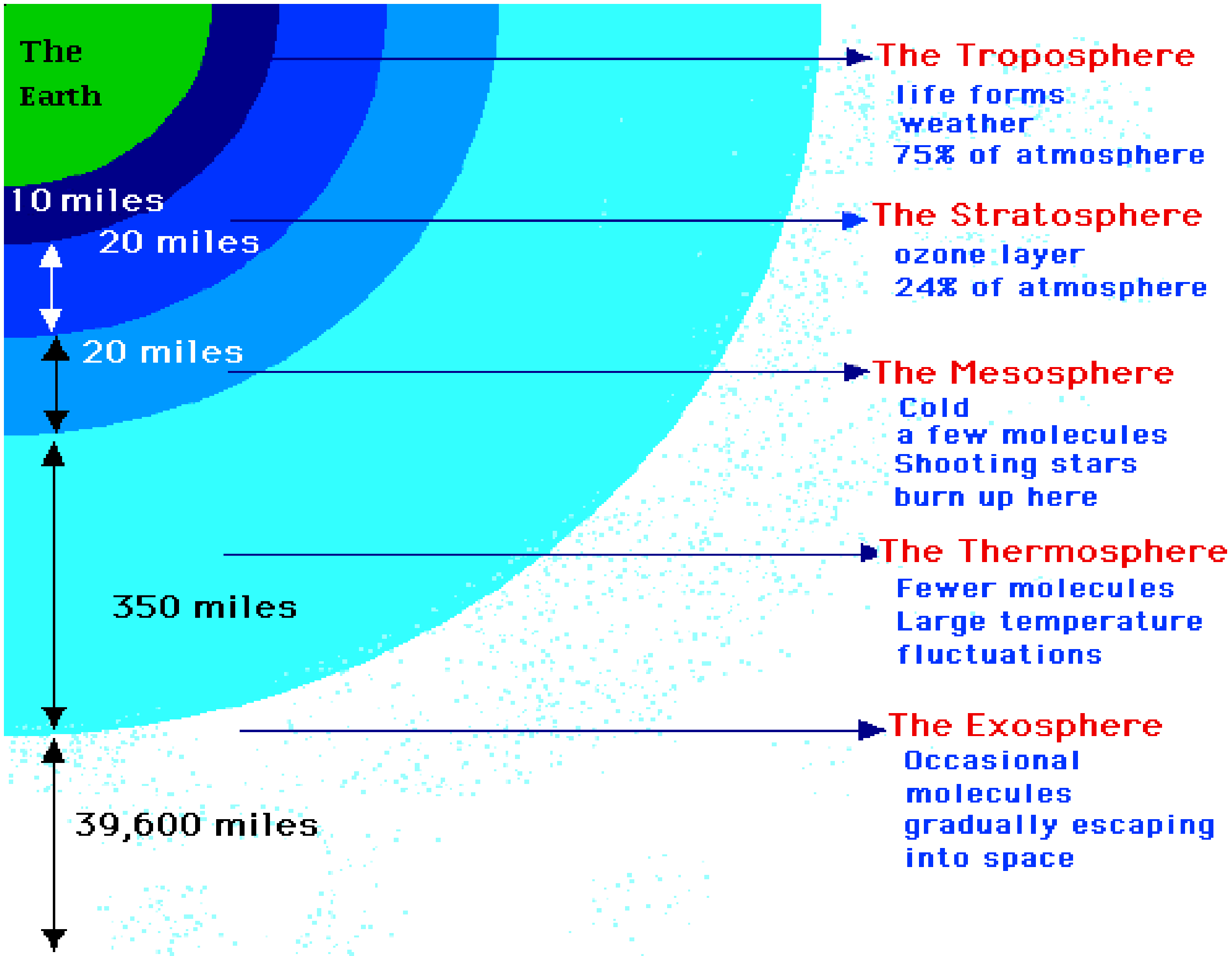
The entire atmosphere of the earth extends out about 40,000 miles (64,000 km) above the earth. The earth is about 8,000 miles (12,800 km) across. The moon is a little less than 240,000 miles (384,000) away[44].



**Above:** The Relative Positions of the earth, the Atmosphere, and the Moon (2,000 miles = 3,200 km; 8,000 miles = 12,800 km; 40,000 miles = 64,000 km; and 240,000 miles = 384,000 km) [44].

The troposphere is the layer of the atmosphere that is closest to the earth; it is the layer in which we live. It is about 10 miles (16 km) deep. Seventy five percent of the mass of all our atmospheric molecules is in the troposphere. This is where we find water vapor, dust, pollen, and soot particles. Weather happens in the troposphere. This layer is turbulent, with storms and atmospheric mixing[44].

In the troposphere, the air cools gradually as it gets further from the earth (about 3.6 degrees Fahrenheit per 1,000 feet or 6.5 degrees Celsius per km[46]). At the very top of this layer the air temperature is about 76 degrees below zero on the Fahrenheit scale (60 degrees below zero on the Celsius scale). This is important because it changes water vapor into ice, forming the cold trap, a temperature region where water vapor stops going up. If we had no cold trap, water molecules would rise in the atmosphere where they would eventually break down into oxygen and hydrogen and escape into space. Without the cold trap earth would loose its water[44].



**Above**. This diagram shows the most important atmospheric layers[44].

The stratosphere lies above the troposphere. It is about twenty miles (32 km) deep. The stratosphere contains about 24% of the mass of all the atmospheric molecules. This layer includes the ozone layer. The ozone layer protects all life on earth from the harmful ultraviolet radiation emitted by the sun. There is not very much ozone -- if it were all together, it would form a layer only three millimeters thick (slightly less than 1/8 of an inch) [44].

The lower part of the stratosphere is cold, but it warms up as it gets farther from the earth -- another effect of the ozone. This layer is peaceful compared to the troposphere.

The troposphere is 10 miles deep and has 75% of the mass of the atmosphere. The stratosphere is 20 miles deep and has 24% of the mass of the atmosphere. This means that the lowest 30 miles (48 km) of the atmosphere has 99% of the mass of the molecules. However, the atmosphere goes out to 40,000 miles (64,000 km). It makes sense, then, that the atmospheric molecules get farther and farther apart as they go up the remaining 39,970 miles (63,952 km). Although there are some atmospheric molecules, they are scattered and occasional, not like our thick ocean of air close to the surface[44].

In the mesosphere, which extends to about 50 miles (80 km), temperature drops again to as low as -173 degrees F (-114 degrees Celsius). Meteors, small pieces of matter drawn to the atmosphere by earth's gravity, become visible to the naked eye as they enter the mesosphere and are heated through friction caused by collisions with air molecules. These "falling stars" usually disintegrate before they reach the earth's surface. Spectacular meteor showers can be observed at certain times of the year when the earth, in its orbit, passes through a swarm of particles generated from the breakup of a comet. The troposphere, stratosphere and mesosphere make up what is called the lower atmosphere[45].

Above 50 miles (80 km) is the upper atmosphere, where air density is extremely rarefied. The thermosphere extends to 400 miles (640 km) and is characterized by large fluctuations of temperature. At these heights there are relatively few molecules and heat retention should be low. However, within the thermosphere solar energy is absorbed and re-radiates heat. At its upper limits the temperature reaches 441 degrees F (227 degrees Celsius)[45].

The exosphere is the outermost layer of the atmosphere, and extends to 40,000 miles (64,000 km) above the earth. It is here that molecules escape from the atmosphere without colliding with other molecules. Throughout the history of our planet most of the lighter molecules have escaped through the exosphere, while the heavier molecules, such as nitrogen and oxygen, have remained[45].

The upper atmosphere can also be divided into regions characterized by exchanges of energy. Extending through both the thermosphere and exosphere is the ionosphere, named for its concentrated layers of ions, electrically charged particles which are responsible for reflecting radio signals. How do we listen to a radio program originating in a city far from our own? The radio waves transmitted from one point on earth reflect off the electrons and return to the surface - but because of the earth's curvature, when they return they are hundreds of miles away from the point of transmission. The waves once again bounce up to the ionosphere, return to the earth, and so on[45].

Above the ionosphere is the magnetosphere, an area in which charged particles are trapped and their behavior dominated by earth's magnetic field. A beautiful example is an aurora, a luminous display of various forms and colors in the night sky. Visible in the Arctic ("northern lights") and Antarctic ("southern lights"), they occur most often during the equinoxes and at times of great sunspot activity. An aurora is thought to be caused by high-speed particles from the sun excited to brightness after colliding with nitrogen and oxygen molecules. Also within the magnetosphere, zones of highly concentrated solar radiation were discovered in the 1980s by the Explorer 1, the first United States artificial satellite. The Van Allen belts, named after the physicist who developed the detectors, circulate along the earth's magnetic field (see glossary for more details on Van Allen belts)[45].

The ionosphere is the ionized component of the earth's upper atmosphere. Although we said that the magnetosphere is above the ionosphere previously (for simplicity of concept), it is not really distinct from the magnetosphere, but rather forms the base of the magnetosphere in terms of electrodynamic processes. The lower boundary of the ionosphere is not well defined but can be taken as about 90 km (56.25 miles) altitude for the present purpose, representing the level where the density of electron-ion pairs falls to roughly $10^{10}$ $m^{-3}$ (for comparison, the average density of air molecules near the earth's surface is $2.7 \times 10^{25}$ $m^{-3}$) and below which electric currents become relatively small. The ionization is formed largely by the effect on the upper atmosphere of solar extreme-ultraviolet and x-ray radiation at wavelengths shorter than

102.6 nm, but energetic particles impacting the upper atmosphere from the magnetosphere also create important enhancements. The ionospheric plasma has a temperature on the order of 1,000 °K (1,340 °F), which is much cooler than the energetic plasma farther out in the magnetosphere. Collisions between charged particles and neutral atmospheric molecules become important below 200 km (125 miles) altitude and strongly affect the electrodynamic characteristics of the ionosphere[13].

Because of the Sun's UV radiation, earth's upper atmosphere is partly (0.1% or less) ionized plasma at altitudes of 70-1,500 km (43.75-937.5 miles). This region, the ionosphere, is coupled to both the magnetosphere and the neutral atmosphere (troposphere). It is of great practical importance because of its effect on radio waves[7].

The role of electrons is noteworthy. The theoretical profiles show that electrons make a negligible contribution to the total conductivity below 50 km (31.25 miles) but completely dominate the conductivity above 60 km (37.5 miles), where they give rise to an extremely steep upward gradient on conductivity (the "equalizing" layer or ionosphere). The electron mobility is so large that the electron contribution to the conductivity becomes equal to the ion contribution at a level where the electron concentration is less than 1 $cm^{-3}$. In this region the model predictions of the electron-ion balance are not trustworthy[13].

The conductivity is greatly reduced at night at all heights above 50 km (31.25 miles). The decrease is partly due to the absence of solar ionizing radiation and partly to changes in neutral chemistry, notably the conversion of atomic oxygen to ozone in the mesosphere. The nighttime equalizing layer lies nearly 10 km (6.25 miles) higher than the daytime layer, and the transition between the two should take place rapidly during twilight[13].

Unlike the outer magnetosphere, the ionosphere behaves as an Ohmic medium, with the current density linearly related to the electric field under most circumstances. The conductivity, however, is highly anisotropic owing to the presence of the geomagnetic field. The conductivity in the direction of the magnetic field is very large, so that the electric-field component in this direction is almost entirely shorted out, and magnetic field lines are nearly electric equipotential lines at all altitudes above 90 km (56.25 miles). The conductivity characteristics perpendicular to the magnetic field depend on the rate of ion-neutral collisions, and they change with altitude as the neutral density varies[13].

> **Historical Note**
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> The discovery of atmospheric conductivity raised a question concerning the origin of the electric fields and the electric currents that were known to exist and flow continuously in the atmosphere. According to the classical picture of the global circuit (Dolezalek, 1972), the total effect of all thunderstorms acting at the same time can be regarded as the global generator, which charges the ionosphere to several hundred kilovolts with respect to the earth's surface. This potential difference drives the air-earth current downward from the ionosphere to the ground in the nonthunderstorm areas through the atmosphere. The value of this air-earth current density (and accordingly the earth's surface potential) varies according to the ionospheric potential and the total columnar resistance between ionosphere and ground[13].

> The downward mapping of the ionospheric electric fields toward the lower atmosphere has been considered previously by a number of researchers. Their studies have all shown that large horizontal-scale electric fields within the ionosphere map efficiently downward in the direction of decreasing electrical conductivity, and that downward electric-field mapping is much more efficient than upward mapping. Researchers showed that the anisotropy of the electrical conductivity can have an important influence on the mapping properties of electric fields. Horizontal electric fields of small-scale size (~1-10 km) are rapidly attenuated as they map downward into the atmosphere from ionospheric heights, but electric fields of larger horizontal scales (~500-1,000 km) map effectively right down to the earth's surface[13], causing a change in the electric potential at earth's surface.
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> **Historical Note Reference**
> Dolezalek, H. (1972). Discussion of the fundamental problem of atmospheric electricity, *Pure Appl. Geophys. 100*, 8-43.

**Solar radiations**

The ionosphere is electrically conducting because the electrons of nitrogen and oxygen molecules in the atmosphere absorb ultraviolet radiation from the Sun. This absorption causes electrons to be dislodged from their molecular orbits, thereby producing free negative charges (electrons) and free positive charges (ions)[5], as explained in more details in the previous section. On the other hand, the solar wind (mainly electrons and protons emitted by the Sun) causes the Aurora Borealis (Australis in the south). These auroras are usually only seen from locations close to the North (or South) magnetic poles. The displays, or aurora storms, take place at altitudes of 100 – 300 km (62.5 – 187.5 miles). The auroral glow is caused by an increase in the number of high energy, charged particles in the solar wind associated with increased solar flare activity. Some of these particles, captured by the magnetosphere (created by the geomagnetic field) are accelerated along the earth's open magnetic field lines (which are only open in the polar regions) and penetrate to the inner Van Allen belt [the inner more energetic, mainly proton, belt centered at 3000 km (1875 miles) above the ground in the magnetosphere] overloading it and causing a discharge of the charged particles into the ionosphere. The discharges extend in narrow belts 20° – 25° or so from each magnetic pole. These changes within the magnetosphere, which cause changes in the ionosphere, may influence weather[1]and the earth's surface electric potential due to mapping down of ionospheric electric fields.

The dramatic increase in middle-atmosphere conductivity during a major solar-proton event causes large changes in the local electric fields at high latitudes. Researchers carried out balloon measurements of the stratospheric electric field over northern Canada during the intense event of August 1972 and reported a decrease in the vertical field by more than an order of magnitude. The decrease closely paralleled the increase in solar-proton flux and could be explained qualitatively by conservation of the fair-weather current in the presence of the greatly enhanced conductivity. The upward mapping of the thunderstorm-generated fields of the lower atmosphere is sensitive to changes in middle-atmosphere conductivity, since the middle atmosphere represents a low-resistance load to the generator even in quiet conditions. The downward mapping of electric fields generated in the ionosphere and magnetosphere, however, is much less sensitive, since the conductivity of the middle atmosphere remains much less than that of the lower ionosphere even during a major solar-proton event[13].

The changes in the global electric circuit arising from the August 1972 solar-proton event (SPE) have been examined in detail by several authors, all of whom pointed out the importance in estimating the changes in middle-atmosphere electrical parameters including the current carried by the precipitating protons themselves in the polar-cap region. Changes in the global circuit, however, arose mainly from the Forbush decrease (see this term in the glossary) in galactic cosmic-ray flux that accompanied the event rather than from the solar-proton flux[13].

## The ionospheric wind

The Sun, besides creating the ionosphere from its UV radiations, has an important role in generating wind in the ionosphere. The ionospheric wind is driven by electric fields that are the main result of the coupling between the magnetosphere (which is very much influenced by the solar wind, see previous section on Solar Radiations) and the ionosphere. While at low-latitudes the ionospheric plasma (ionized gas in the ionosphere) is co-rotating with the earth, at higher latitudes it is convecting under the influence of the large-scale magnetospheric electric fields mapped to low altitudes. The convection pattern leads to ionospheric Hall currents (one type of ionic drift mechanisms part of the ionospheric dynamo that generates currents in the ionosphere; see drift mechanisms in the glossary), and along the auroral oval (auroras are generally located within oval shaped regions around both geomagnetic poles of the earth) so-called convection electrojets (large horizontal currents that flow in the ionosphere) are formed at about 100 km (62.5 miles) altitude: eastward electrojet on the duskside, westward on the dawnside. The coupling between the ionosphere and magnetosphere results also into large and small-scale currents aligned with the magnetic field called field-aligned currents (FACs). As the down and upward parts of the current systems are typically separated, horizontal current systems must be formed within the conducting ionosphere[7].

Winds in the ionospheric dynamo region have the effect of moving an electric conductor (the weakly ionized plasma) through a magnetic field (the geomagnetic field), which results in the production of an electromotive force and the generation of electric currents and fields. Thus we may consider that two components of current exist, one driven by the “real” (measurable) electric field and the other driven by the “dynamo electric field” which is the product of the velocity of the plasma and the strength of the local geomagnetic field (creating the ionospheric dynamo region). These two components are not independent, however because it turns out that the electric field itself depends on the dynamo electric field[13].

Winds in the upper atmosphere change strongly through the course of the day. They are driven in one form or another by the daily variation in absorption of solar radiation. Atmospheric heating causes expansion and the creation of horizontal pressure gradients, which drive the global-scale upper-atmospheric winds. Solar-ultraviolet radiation absorption at the height of the dynamo region drives a major portion of the winds. Absorption by ozone lower down [30-60 km (18.75-37.5 miles) altitude] also affects the dynamo-region winds by generating atmospheric tides that can propagate upward as global-scale atmospheric waves. Important contributions to the ionospheric dynamo also come from altitudes above 130 km (81.25 miles), where the conductivity is smaller but where winds tend to be stronger and to vary less in height[13].

## Solar wind - magnetosphere - ionosphere - thermosphere coupling

One of the main tasks in space physics is to explain the various ways the Sun/solar wind, magnetosphere, ionosphere, and even upper atmosphere (thermosphere) are coupled to each other. This coupling explains how the electric potential of the ionosphere changes over time. This change in ionospheric potential affecting the earth's surface potential can be understood in at least tree ways:

1) The ionosphere and the earth's surface form the two plates of a capacitor and so variation of potential at one plate will be reflected at the other plate and

2) As the earth rotates underneath the Sun, periodic differential heating of the atmosphere causes it to expand on the day-side and contract on the night-side. Superimposed upon this variation is an atmospheric tide, similar to the oceanic tide and driven most substantially by the rotation of the earth under the gravitational field of the Moon. The combination of these periodic forces drive winds in the ionosphere, and with the resulting fluid motion across magnetic-field lines, electric currents are induced. These currents support their own magnetic fields, and thus a diurnal perturbation in the geomagnetic field is generated. The diurnal-field variation can be measured at the earth's surface, and with an array of magnetometers it is possible to map the electric currents in the ionosphere[8].

3) Ionospheric potential variations, if large enough, map right down to earth's surface, as explained previously.

### Solar wind – magnetosphere coupling[13]

The solar wind is a plasma with electron and ion number of the order of $5 \times 10^6$ $m^{-3}$ flowing continually outward from the Sun at a speed of 300 -1000 km/sec (675,000-2,225,000 m/h). Imbedded within it is the interplanetary magnetic field (IMF), which is maintained by electric currents flowing throughout the solar-wind plasma. The IMF strength at the orbit of the earth is roughly a factor of $10^{-4}$ smaller than the strength of the surface geomagnetic field. Most of the time, an interplanetary field line near the earth can be traced back to the surface of the Sun, where magnetic fields are ubiquitous. As the Sun rotates (once every 27 days) different magnetic regions influence the IMF near the earth. The combination of solar-rotation and outward solar-wind flow produce a roughly spiral IMF pattern. In addition, the solar-wind velocity can change dramatically and produce both large-scale and small-scale distortions of the IMF so that the field direction and strength vary greatly. These changes have been found to influence the electrical state of the magnetosphere.

In an analogy with a dynamo – an electric machine that generates electricity by rotating a conducting armature through a magnetic field - the motion of a plasma through a magnetic field produces an electromotive force (emf) and current flow and can also be considered a dynamo. The solar wind/magnetosphere dynamo results from the flow of the solar wind around and partly into the magnetosphere, setting up plasma motion in the magnetosphere as well as electric fields and currents.

Magnetospheric plasma convection has a number of important consequences, one of which is the energization of plasma and particle precipitation into the ionosphere. As plasma flows from the tail toward the earth it is compressionally heated because the volume occupied by plasma on neighboring magnetic-field lines is reduce as the magnetic-field strength increases and as the length of field lines decreases. Other particle acceleration processes also help to energize the plasma. Some of the energized particles precipitate into the ionosphere and create ionization enhancements, especially in the auroral oval. The energized plasma also has important influence on the flow of electric currents and on the distribution of electric fields. Energetic particles drift in the earth's magnetic field – electrons toward the east and positive ions toward the west – so that a westward current flows within the hot plasma. This westward current, flowing in the geomagnetic field, essentially exerts an electromagnetic force on the plasma directed away from the earth and thus tending to oppose the earthward convection. Charge separation associated with the current tends to create an eastward electric-field component, opposite to the nightside westward convection electric field, largely canceling the convection electric fields in the inner magnetosphere.

Currents are an integral part of the electrical circuit associated with the solar wind/magnetosphere dynamo. Currents flowing along the direction of the magnetic field (field-aligned currents or FACs) couple the auroral oval with outer portions of the magnetosphere. The upward and downward currents are connected by cross-field currents in the ionospheric dynamo region. The anisotropy of the dynamo-region conductivity gives rise to strong current components perpendicular to the electric field in the auroral oval, in the form of eastward and westward auroral electrojets.

**Historical Note**
D'Angelo et al. (1982) processed over 1,200 hours of stratospheric balloon data and correlated the vertical electric field with magnetic activity parameters. During quiet geomagnetic conditions the classical Carnegie curve was reproduced. During more active geomagnetic conditions, however, the dawn-dusk potential difference of the magnetospheric convection pattern was shown clearly to influence the fair-weather field. The above measurements suggest an electrical coupling between the magnetospheric dynamo and the global electrical circuit and indicate a need for more measurements[13].

**Historical Note Reference**
D'Angelo, N., I. B. Iversen, and M. M. Madsen (1982). Influence of the dawn-dusk potential drop across the polar cap on the high-latitude atmospheric vertical current, *Geophys. Res. Lett. 9*, 773-776.

## Magnetosphere – ionosphere coupling

The ionosphere is the ionized component of the earth's upper atmosphere. It is not distinct from the magnetosphere, but rather forms the base of the magnetosphere in terms of electrodynamic processes. The lower boundary of the ionosphere is not well defined but can be taken as about 90 km (56.25 miles) altitude for the present purpose, representing the level where the density of electron-ion pairs falls to roughly $10^{10}$ $m^{-3}$ and below which electric currents become relatively small. The ionization is formed largely by the effect on the upper atmosphere of solar extreme-ultraviolet and x-ray radiation at wavelengths shorter than 102.6 nm, but energetic particles impacting the upper atmosphere from the magnetosphere also create important enhancements. The ionospheric plasma has a temperature on the order of 1,000 °K (1,340 °F), which is much cooler than the energetic plasma farther out in the magnetosphere. Collisions between charged particles and neutral atmospheric molecules become important below 200 km (125 miles) altitude and strongly affect the electrodynamic characteristics of the ionosphere[13].

The ionosphere and magnetosphere are closely linked together via magnetic field lines. Magnetospheric electric fields map down to the ionosphere, creating, e.g., plasma convection, frictional heating and plasma instabilities. Auroral particle precipitation ionizes the high latitude atmosphere also during nighttime, and heat can be conducted from the magnetosphere down to the ionosphere. On the other hand, some of the cold ionospheric electrons and ions evaporate into the plasmasphere (the plasma region just above the ionosphere that is part of the magnetosphere), plasma sheet and tail lobes. The changed magnetospheric ion composition (especially increased $O^+$) can have large effects on some important magnetospheric processes[8].

### Ionosphere – thermosphere coupling

Collisions between the convecting ionospheric plasma and the neutral atmosphere leads to generation of neutral winds and Joule heating of the neutral gas. Neutral gas can be further heated by plasma instabilities that arise due to the ionospheric currents. These phenomena leads to changes in weather[8].

### Variability in the solar wind - magnetosphere - ionosphere - thermosphere coupling[10]

Because the solar wind and particularly the IMF undergo large variations, it is not surprising that the electric fields associated with solar wind/magnetosphere dynamo action similarly show large variations. The interconnection of the interplanetary and magnetospheric magnetic fields maximizes when the IMF is southward. As the IMF direction rotates the amount of interconnected magnetic flux appears to lessen. For a northward-directed IMF the pattern of magnetic-fields interconnection must be quite different from a southward-directed IMF, and it is possible that interconnection becomes insignificant, so that the magnetosphere is closed. The east-west component of the IMF affects the interconnection morphology and consequently also the pattern of high-latitude magnetosphere convection. The third IMF component, directed toward or away from the Sun, seems to have a less important role in the solar wind/magnetosphere dynamo than the other two components. However, the toward/away component correlates strongly with the west/east IMF component because of the tendency for the IMF to assume a spiral pattern around the Sun.

Magnetic storms are dramatic disturbances of the entire magnetosphere lasting a time on the order of 1 day, usually produced by a strong enhancement of the solar-wind velocity, density, and/or southward IMF component. The enhancement often comes from explosive eruptions of plasma near the Sun's surface but enhancements are sometimes a long-lasting, relatively localized feature of the solar wind that sweeps past the earth as the Sun rotates. During a magnetic storm, magnetospheric convection varies strongly but is generally enhanced; plasma energization and precipitation into the ionosphere are greatly increased; and electric current flow is much stronger, also varying rapidly in time.

Perturbations of ground-level geomagnetic field up to a few percent of the total geomagnetic-field strength can occur during a magnetic storm. Storms are composed of a succession of impulsive disturbances lasting 1-3 hours, called substorms. Impulsive disturbances with similar characteristics also occur on the average a few times a day even when no storm is in progress, and these are also called substorms. The characteristics of substorms can vary quite considerably from one to another but are often associated with what appears to be a large-scale plasma instability in the magnetospheric tail. The disturbed electric fields extend beyond the auroral oval and can even be seen at the magnetic equator.

Magnetic storms are predominantly a phenomenon of the solar wind/magnetosphere dynamo, but they affect the ionospheric wind dynamo as well. In addition to strong auroral conductivity enhancements, conductivities can also be altered at lower latitudes at night by over an order of magnitude, though they still remain well below daytime values. The nighttime ionospheric layer above 200 km (125 miles) altitude can be raised or lowered in response to stormtime electric fields and winds, which changes its conductive properties. During major storms the entire wind system in the dynamo region can be altered by the energy input to the upper atmosphere, so that the pattern of electric-field generation is modified. This effect can raise the potential at the equator by several thousand volts with respect to high latitudes.

Regular changes in the electric fields and currents occur over the course of the 11-year solar cycle and with the changing seasons. Ionospheric conductivities change by up to a factor of 2 as the ionizing solar radiation waxes and wanes along with the trend of sunspots. Ionospheric winds also change as the intensity of solar extreme-ultraviolet radiation increases and decreases. We know that ionospheric dynamo currents change by a factor of 2 to 3 with the solar cycle, but the variation of electric fields is not yet so extensively documented.

Rapid variations with time scales ranging from seconds to hours are a common feature of ionospheric electric fields and currents. The magnitude of the fluctuations is often as large as that of the regular daily variations, generally increasing with magnetic latitude up to the auroral oval. Besides storm and substorm phenomena, global-scale disturbances in the electric fields and currents also occur with the arrival of solar-wind shocks, with fluctuations of the IMF, and with rapid ionosphere conductivity changes during solar flares. Localized ionospheric electric-field fluctuations may be associated with wind or conductivity irregularities or with small-scale magnetospheric processes. For example, localized quasi-periodic oscillations in the electric fields and currents with periods ranging from a fraction of a second to minutes, called pulsations, are often observed at high latitudes.

The ionosphere is affected in many ways by electric fields. Above 200 km (125 miles), where the chemical lifetimes of ions range from several minutes to hours, rapid convection of ionization at high latitudes can bring dense dayside plasma to the nightside of the earth in some places, cause stagnation and prolonged nighttime decay of ionization at other places, and generally produce highly complex patterns of ionization density. Plasma temperatures and chemical reaction rates are also affected by the rapid ion convection through the air. Even at middle and low latitudes plasma drifts have an important influence on the upper ionosphere, primarily by raising or lowering the layer into regions of lower or higher neutral density, so that chemical decay is retarded or accelerated. During magnetic storms the plasma-drift effects on the ionosphere are not only intensified but are also supplemented by indirect effects through modification of the neutral atmosphere. Auroral heating induces atmospheric convection that alters the molecular composition of the upper atmosphere and leads to more rapid chemical loss of the ionization, even at middle latitudes. Winds generated by the magnetic storm impart motion to the ionization along the direction of the magnetic field, causing redistribution of the plasma as well as further modification of the loss rate. All these ionospheric phenomena affect radio-wave transmissions that reflect off the ionosphere. They also reflect on the earth’s surface electric potential.

## V. Overall Influences on Earth's Surface Electric Potential

As the earth rotates around the Sun, periodic differential heating of the atmosphere causes it to expand on the day-side and contract on the night-side. Superimposed upon this variation is an atmospheric tide, similar to the oceanic tide and driven most substantially by the rotation of the earth under the gravitational field of the Moon. The combination of these periodic forces drives winds in the ionosphere and with the resulting fluid motion across magnetic-field lines, electric currents are induced[5]. These electric currents circulate from high potential regions to low potential regions in the ionosphere. Because of the capacitive coupling between the earth's surface and the ionosphere, the earth's surface potential increases or decreases as a reflection of variations in the ionosphere. This is the major cause of periodical electric potential variations in the fair whether regions (when there is no geomagnetic storm, no volcanic or earthquake activity, and away from man-made structures). In the thunderstorm regions, apart from the Cb clouds, the atmosphere carries a net positive charge and the electric potential increases with height, and in cloud and fog. Strong electrical forces also exist in and around rain showers which can transfer a charge of either polarity to the earth surface[1]. The electrostatic structure within Cb clouds is such that pockets of different charge exist throughout the cloud but, in 90% or more, with a main net positive charge residing on the cloud ice crystals in the upper part of the cloud and a main net negative charge, of similar magnitude, centered near the middle or lower part of the cloud at the sub-freezing level, the charge mainly residing on super-cooled droplets. The electrostatic forces of repulsion/attraction induce secondary charge accumulations outside the cloud, a positive electric potential region on the earth's surface directly below the cloud[1]. This positive charge accumulation region below the cloud maintains the increase in potential at the earth's surface for as long as the cloud maintains its electrical charge.

The electric field at the ground is a readily measurable quantity that has been determined at various stations for a century. In fair weather, the electric field is directed downward perpendicular to the ground and is typically 100 -150 V/m. Field reversals are rare during undisturbed periods, but they are frequent during stormy weather and in conditions of dust, smoke, and fog. The electric field in densely populated areas is usually much larger than 150 V/m, whereas in small towns and far away from cities it can be smaller. The main reason for the variability of the electric field near the ground is that it is a complex quantity subject to Universal Time variations of the global circuit as well as the local influences of turbulence, weather, smoke, aerosols, and other anthropogenic factors[10].

Israël (1973)[47] summarized electric-field observations that define (a) a latitudinal variation; (b) altitude variations including effects of clouds and aerosol layers; (c) diurnal variation giving continental and oceanic types; (d) annual variation with maximum values during southern hemisphere summer; and (e) possible variation due to solar influences. In fair weather the ground electric field (and correspondingly the earth's surface electric potential) varies owing to changes in columnar resistance, ionospheric potential, and the local electrical conductivity at the ground. During disturbed periods it fluctuates rapidly due to the space-charge variation associated with turbulence, lightning, thunderstorm charge location, precipitation in the form of snow or rain, cloud passages, fog, blowing snow, dust or aerosols, and other meteorological properties. The relationship of the ground electric field to these processes has been studied extensively. More recently, the rapid variation of electric field observed at a number of ground stations has been used to derive the charge structure within clouds[10].

Typically the vertical electric field strength decreases exponentially with altitude during fair weather. During cloudiness without precipitation and during haze and fog variations are much more pronounced and are mainly caused by conductivity variations, especially in the lower troposphere, rather than by variations of the ionospheric potential itself. At a typical continental station during fair weather the variation of the vertical electric field strength is small with a mean value of about 120 V/m with no negative fields. During haze and fog the variations become much larger and even negative values (resulting in a reversal of the earth's surface electric potential) occur indicating the presence of space charges around the station. The higher positive vertical electric field strength values are mainly caused by a drastic reduction of the atmospheric conductivity due to the attachment of small ions to haze or fog droplets. The highest values of the vertical electric field strength are measured during rain or snow showers and thunderstorms. The highest field values can reach 5,000V/m at the ground. This seems to be an upper limit because corona discharges build up a space-charge layer with the appropriate sign so as to reduce the original field values[10].

At globally representative stations the air-earth current density shows a diurnal variation versus universal time with a minimum at around 0300 GMT (Greenwich Mean Time) and a maximum near 1800 GMT, reflecting the diurnal variations of the ionospheric potential. The agreement between these stations strongly supports the concept of an universally controlled global circuit. Also at globally representative stations, such as ocean or polar stations, the vertical columnar resistance remains nearly constant during fair weather. Here the electric field strength near the ground (and the earth's surface potential) shows a diurnal variation with universal time similar to that shown for the air-earth current density, both reflecting variations of the ionospheric potential. Over the continents consideration must be given to a varying ionization rate in the first few hundred meters caused by the exhalation of radioactive materials from the earth. This ionization rate depends strongly on different meteorological parameters, such as convection, and therefore the columnar resistance can no longer be regarded as constant. The global diurnal variation of the electric field is normally masked by local variations at these stations. If local generators, such as precipitation, convection currents, and blowing snow or dust, also become active, the description becomes increasingly complicated and the vertical electric field strength can vary considerably[10].

Rapid magnetic fluctuations caused by changing ionospheric currents disturb geophysical surveys of magnetic anomalies in the earth's crust. In addition, the fluctuations induce electric currents in the earth. Analysis of the earth currents can be useful for geophysical studies, but when they enter large man-made structures like electric transmission lines and pipelines they can cause disruptive electrical signals and corrosion (see section on Interactions of Telluric Currents with Man-Made Systems)[10]. Selected examples of the observed influences of different types of phenomena follow.

### Solar Radiations

A good example of how the earth's surface potential can be affected by solar radiations and ionospheric winds is to study the effect of geomagnetic storms on electric power grids. The discussion that follows is from Kappenman[9]. The sprawling North American power grid resembles a large antenna, attracting electric currents induced by giant solar storms. Severe space weather occurring during solar cycles has the potential to cause a large-scale blackout in North America. When the earth's magnetic field captures ionized particles carried by the solar wind, geomagnetically induced currents (GIC) can flow through the power system, entering and exiting the many grounding points on a transmission network. GICs are produced when shocks resulting from sudden and severe magnetic storms subject portions of the earth's surface to fluctuations in the planet's normally stable magnetic field and electric potential. These fluctuations induce electric fields in the earth that create potential differences in voltage between grounding points—which causes GICs to flow through transformers, power system lines, and grounding points. Only a few amps are needed to disrupt transformer operation, but over 100 amps have been measured in the grounding connections of transformers in affected areas. For example the great geomagnetic storm of March 13, 1989, plunged the entire Hydro-Québec system, which serves more than 6 million customers, into a GIC-triggered blackout. Most of Hydro-Québec's neighboring systems in the United States came close to experiencing the same sort of outage. Many portions of the North American power grid are vulnerable to geomagnetic storms. Much of the grid is located in northern latitudes, near the north magnetic pole and the auroral electrojet current and in regions of igneous rock, a geological formation with high electrical resistivity (figure below).

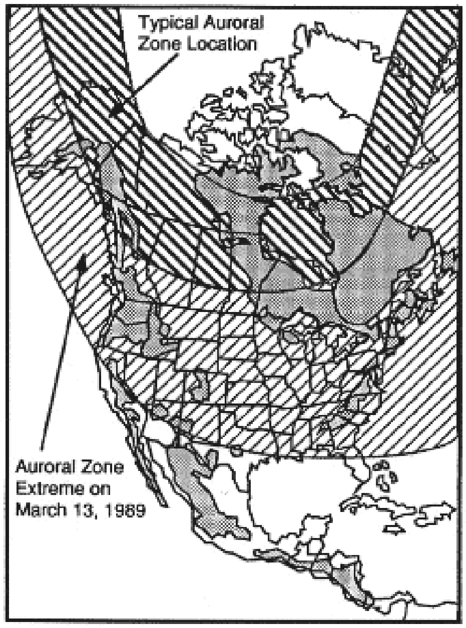

Diagram Above: Power systems in areas of igneous rock (gray) are the most vulnerable to the effects of intense geomagnetic activity because the high resistance of the igneous rock encourages geomagnetically induced currents (GICs) to flow in the power transmission lines situated above the rock. Shown in cross-hatching are the auroral zone and the extremes that the aurora can reach during severe disturbances such as March 13, 1989.

Systems in the upper latitudes of North America are at increased risk because auroral activity and its effects center on the magnetic poles, and the earth's magnetic north pole is tilted toward North America. The electric power network depends on remote generation sources linked by long transmission lines to delivery points. The effects of GICs build cumulatively over a large geographic scale, overwhelming the capability of the system to regulate voltage and the protection margins of equipment. The Hydro-Québec outage resulted from the linked malfunction of more than 15 discrete protective-system operations. From the initial event to complete blackout, only one-and-a-half minutes elapsed—hardly enough time to assess what was occurring, let alone intervene. The Québec outage did not, in this instance, cascade beyond the province's borders. But if the disturbance had occurred under higher load conditions (nearer to summer or winter peak demand conditions, for instance), cascading outages might have spread across a region of the northeastern United States extending to the Washington D.C. area. Oak Ridge National Laboratory assessed the potential impact of a widespread blackout in the northeastern United States from a geomagnetic storm event slightly more severe than the March 1989 blackout as a $3–6 billion loss in gross domestic product. This figure does not account for the potential disruption of critical services such as transportation, fire protection, and public security. Other assessments placed the 1989 and 1991 geomagnetic storm effects in a category equivalent to Hurricane Hugo and the San Francisco earthquake in their relative impact on the reliability of the electric power grid. Faced with operating power systems in earth's uncontrolled natural laboratory, the power industry and the scientific community are working to develop a better understanding of the causes and effects of this phenomenon. The scale of the problem is immense: the physical processes entail vast volumes and uncertainties of the magnetosphere, the ionosphere, the Sun and the 93 million miles of interplanetary space to the earth. A paucity of data limits our abilities to develop accurate models and understand the relationships between the power grid configuration, the underlying geological features, and their coupling to the fluctuations of the geomagnetic field and surface electric potential. A set of numerical models can accurately compute the electric fields induced in the earth from the disturbed geomagnetic field and a map of the deep earth conductivity. The induced current entering various points in a power network can then be determined from computed electric fields. The measured electric fields near Forbes, a major substation in northern Minnesota, and the measured induced currents flowing in the grounding points of transformers connected to two long transmission lines during a 30-minute period shows very good correlation.

### Rain

During rain or snow and especially in thunderclouds, the scatter in the vertical electric field values becomes very large, including regions with large negative field values. Temporal variations are fast, and the horizontal components of the electric field strength can reach the same order of magnitude as the vertical components. These large variations of the electric field strength in shower and thunderclouds are caused by regions of high-space-charge density of both signs in these clouds ground[10].

### High-Voltage Power Lines

Near a high-voltage power line (220 kV) the electric field values near the ground can be higher by as much as 150 V/m compared with the electric field at an undisturbed station. Vertical electric field values can be disturbed near large cities. As an example, a station at the south edge of a large city in Germany (Augburg) shows almost a fair-weather field pattern, the values at the northern station (inside the northern part of the city) exhibit large variations, and even negative values of the electric field (this means a polarity reversal of the earth's surface electric potential). The reason for large variations at the disturbed stations is, in both cases, drifting pollution and/or space charges. Above the ground the vertical electric field drops rapidly with increasing altitude owing to the increasing atmospheric conductivity[10].

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# GLOSSARY

**Alpha particle:** (Or α -particle; symbol $^4He_2^{++}$.) Physically indistinguishable from the nucleus of a helium atom—two protons and two neutrons bound together by nuclear forces—but usually restricted to the product of nuclear reactions. For example, alpha particles with energies of several million electron volts are emitted in the radioactive disintegration of naturally occurring isotopes of uranium and thorium. The alpha particle carries a positive charge twice the magnitude of the electron charge. Alpha particles are important in atmospheric electricity as one of the agents responsible for atmospheric ionization. Compare beta particle, gamma ray.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=alpha-particle1)

**Alpha ray:** (Or alpha radiation.) A stream of alpha particles; can also mean a single alpha particle.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=alpha-ray1)

**Asthenosphere :** Region in the upper mantle of the earth's interior, characterized by low-density, semi-plastic (or partially molten) rock material chemically similar to the overlying lithosphere. The upper part of the asthenosphere is believed to be the zone upon which the great rigid and brittle lithospheric plates of the earth's crust move about (see plate tectonics). The asthenosphere is generally located between 45 - 155 miles (72 - 250 km) beneath the earth's surface, though under the oceans it is usually much nearer the surface and at mid-ocean ridges rises to within a few miles of the ocean floor. Although its presence was suspected as early as 1926, the worldwide occurrence of the plastic zone was confirmed by analyses of earthquake waves from the Chilean earthquake of May 22, 1960. The seismic waves, the speed of which decreases with the softness of the medium, passed relatively slowly though the asthenosphere, thus it was given the name Low Velocity zone, or the Seismic Wave Guide (see seismology). Deep-zone earthquakes, i.e., those that occur in the asthenosphere or below it, may be caused by crustal plates sinking into the mantle along convergent crustal boundaries.
(Reference: http://education.yahoo.com/reference/encyclopedia/entry?id=3144)

**Atmosphere:** earth's atmosphere consists of nitrogen (78.1%) and oxygen (20.9%), with small amounts of argon (0.9%), carbon dioxide (variable, but around 0.035%), water vapor, and other gases. The atmosphere protects life on earth by absorbing ultraviolet solar radiation and reducing temperature extremes between day and night. 75% of the atmosphere exists within 11 km (7 miles) of the planetary surface. As the atmosphere has no abrupt cut-off, but rather thins gradually with increasing altitude, there is no definite boundary between the atmosphere and outer space. In the United States, persons who travel above an altitude of 50 miles (80 kilometers) are designated as astronauts. 400,000 feet (75 miles or 120 kilometers) marks the boundary where atmospheric effects become noticeable during re-entry. The altitude of 100 kilometers or 62 miles is also frequently used as the boundary between atmosphere and space.

*Temperature and the atmospheric layers*

Conventional usage divides the atmosphere into layers on the basis of the average temperature profile. The stratosphere is the region of positive vertical temperature gradient extending from the tropopause to a height of about 50 km, and the overlying region of negative temperature gradient is the mesosphere, extending to about 85 km altitude, where the lowest temperatures in the atmosphere are reached. The main heat source in both of these regions is provided by absorption of solar-ultraviolet radiation by ozone. At still greater heights lies the thermosphere, in which absorption of extreme-ultraviolet radiation causes the temperature to increase again with height[10].

The relationship between temperature and altitude varies between the different atmospheric layers:

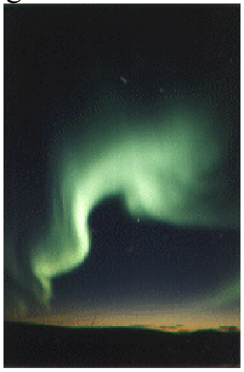
- troposphere - 0 - 7/17 km (0 - 4/11 miles), temperature decreasing with height.

- stratosphere - 7/17 - 50 km (4/11 – 31 miles), temperature increasing with height.
- mesosphere - 50 - 80/85 km (31 – 50/53 miles), temperature decreasing with height.
- thermosphere - 80/85 – 640+ km (50/53 miles – 400+ miles), temperature increasing with height.

The boundaries between these regions are named the tropopause, stratopause, and mesopause. The average temperature of the atmosphere at the surface of earth is 14 °C. (Reference: http://www.free-definition.com/earths-atmosphere.html)

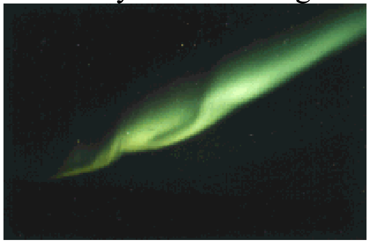
**Atmospheric electricity:** 1. Electrical phenomena, regarded collectively, that occur in the earth's atmosphere. These phenomena include not only such striking manifestations as lightning and St. Elmo's fire, but also less noticeable but more ubiquitous effects such as atmospheric ionization, the air-earth current, and other quiescent electrical processes. The existence of separated electric charges in the atmosphere is a consequence of many minor processes (spray electrification, dust electrification, etc.) and a few major processes (cosmic-ray ionization, radioactive-particle ionization, and thunderstorm electrification). The details of thunderstorm charge separation are poorly understood. The maintenance of the prevailing atmospheric electric field is now widely believed to be due to thunderstorm effects. 2. The study of electrical processes occurring within the atmosphere.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=atmospheric-electricity1)

**Aurora:** Geomagnetic field lines can guide energetic electrons and protons from magnetosphere or magnetosheath down to earth's atmosphere. Precipitating particles loose their energy via collisions with the neutral particles and ionize them at approximately the same altitude range than solar UV radiation when creating the ionosphere. In addition, some of the atmospheric constituents are excited to higher energy levels: this can lead to emission of auroral light. Most of this activity occurs within the auroral oval (the major exceptions being the sun-aligned arcs and low-latitude aurorae).



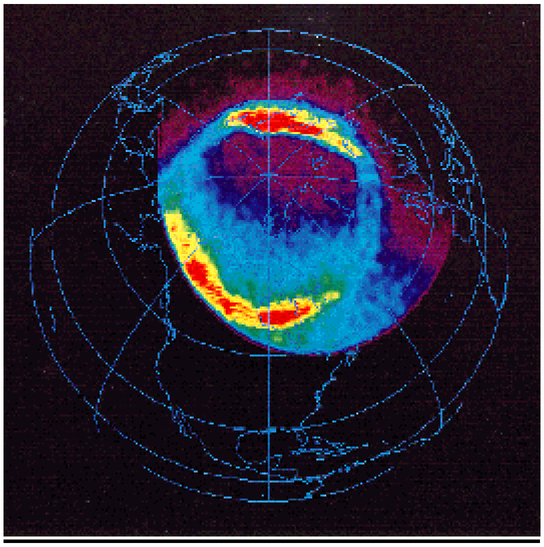
(Reference: http://www.oulu.fi/~spaceweb/textbook/auroras.html.)

**Auroral arcs:** Auroral arcs are luminous bands elongated in east-west direction. Their thickness (in the ionosphere) is typically several (or even tens of) kilometers. However, embedded in an arc one finds structures or elements of finer scale, down to tens of meters only. Arcs drift often in north-south direction. During increased geomagnetic activity arcs tend to get deformed.



(Reference: http://www.oulu.fi/~spaceweb/textbook/aurora/arc/.)

**Auroral ovals:** Geographically, most auroras are located within oval shaped regions around both geomagnetic poles of the earth (however, see also sun-aligned arcs). Although the existence of these auroral ovals was derived from the early ground-based observations, they were imaged for the first time by the Dynamic Explorer 1 satellite (DE-1) in the early 1980's (the figure below is from the Polar UltraViolet Imager: foreground is dayside). The ovals are displaced relatively to the magnetic poles such that they extend further towards equator at the midnight sector. The regions that are left inside the ovals are called the polar caps. While the magnetic field lines within the polar caps are open, i.e., they are connected to earth only on one end, the field lines inside the oval (and at lower latitudes) are closed. Because of this, the auroras on northern and southern oval region can be mirror images of each other. The diameter of the ovals depends on the amount of the open flux in the polar cap: during active periods, especially during major geomagnetic storms, the ovals expand to lower latitudes. Although the latitudinal width of the oval is rather small (about 10°), it maps, in the nightside, to a spatially vast region in the plasma sheet and plasma sheet boundary layer (PSBL). The enhanced activity in the upper part of the figure corresponds to a nightside substorm. This can lead to a formation of a double oval structure at the last stage of the substorm activity or during the recovery phase. At the same time the figure shows how intense the dayside auroras can be.



(Reference: http://www.oulu.fi/~spaceweb/textbook/oval.html.)

**Basement:** The rock layer below which economic hydrocarbon reservoirs are not expected to be found, sometimes called economic basement. Basement is usually older, deformed igneous or metamorphic rocks, which seldom develops the porosity and permeability necessary to serve as a hydrocarbon reservoir, and below which sedimentary rocks are not common. Basement rocks typically have different density, acoustic velocity, and magnetic properties from overlying rocks.
(Reference: http://www.glossary.oilfield.slb.com/Display.cfm?Term=basement)

**Beta particle:** (Or β particle) Physically indistinguishable from the electron (or positron) but usually restricted to products in nuclear reactions (beta decay). The term was coined by Ernest Rutherford, who discovered that the ionizing radiation emitted by uranium consisted of "at least two distinct types . . . one that is very readily absorbed . . . the α radiation, and the other of a more penetrative character . . . the β radiation." Kinetic energies of beta particles range from tens of thousands to millions of electron volts.

Because either electrons or positrons are emitted in beta decay, the term beta particle, a relic of an era in which its identity was unknown, is falling into disuse. See alpha particle, gamma ray.
From: Boorse, H. A., and L. Motz, 1966: The World of the Atom, Vol. I, 437–445.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=beta-particle1)

**Beta ray:** (Or beta radiation.) A stream of beta particles; can also mean a single beta particle.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=beta-ray1)

**Bow shock:** As first proposed by Axford (1962) and Kellogg (1962), all planetary bodies having either a magnetosphere or a highly conducting ionosphere have also a bow shock associated with the deflection of the solar wind around them. This shock wave develops because the information needed to deflect the solar wind plasma around the obstacle travels at a velocity that is less than that of the solar wind flow. In general three waves are needed:

- slow magnetosonic wave
- intermediate wave
- fast magnetosonic wave.

It is the last, fast magnetosonic wave that creates the bow shock also in front of the earth 's magnetosphere. The other two waves are present in the magnetosheath.
(Reference: http://www.oulu.fi/~spaceweb/textbook/bowshock.html.)

**Clastic:** 1- Separable into parts or having removable sections: a clastic anatomical model.
2- Geology. Made up of fragments of preexisting rock; fragmental.
(Reference: http://dictionary.reference.com/search?r=2&q=clastic)

**Cloud discharge:** See cloud flash.

**Cloud flash:** (Also called intracloud flash, cloud-to-cloud flash.) A lightning discharge occurring between a positively charged region and a negatively charged region – both of which may lie in the same cloud. The most frequent type of cloud discharge is one between a main positively charged region and a main negatively charged region. Cloud flashes tend to outnumber cloud-to-ground flashes. In general, the channel of a cloud flash will be wholly surrounded by cloud. Hence, the channel's luminosity typically produces a diffuse glow when seen from outside the cloud and this widespread glow is called sheet lightning. (Reference: http://amsglossary.allenpress.com/glossary/search?id=cloud-flash1)

**Cloud-to-ground discharge:** See cloud-to-ground flash.

**Cloud-to-ground flash:** A lightning flash occurring between a charge center in the cloud and the ground. On an annual basis, negative charge is lowered to the ground in about 95% of the flashes. The remaining flashes lower positive charge to the ground. This type of lightning flash, which can be contrasted with an intracloud flash or cloud flash, consists of one or more return strokes. The first stroke begins with a stepped leader followed by an intense return stroke that is the principal source of luminosity and charge transfer. Subsequent strokes begin with a dart leader followed by another return stroke. Most of the strokes use the same channel to ground. The time interval between strokes is typically 40 μs.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=cloud-to-ground-flash1)

**Columnar resistance:** In atmospheric electricity, the electrical resistance of a column of air 1 meter square, extending from the earth’s surface to some specified altitude. Measurements extending to an altitude of 18 km (11 miles) indicate that the atmospheric columnar resistance to that height amounts to

about $10^{17}$ ohm/m$^2$. Probably, this is only slightly less than the total columnar resistance from earth to ionosphere. In fact, roughly half of the total columnar resistance from the earth to 18 km is contributed by the lowest 3 km (1.9 miles) of the column where, in addition to the greater density of the air, the high concentration of atmospheric particulates leads to a relatively high population of poorly conducting large ions rather than the more mobile small ions. Total columnar resistance does not vary greatly with either time or locality. By contrast, the columnar resistance of the lowest fraction of a kilometer (or a mile) varies greatly, causing fluctuations in the atmospheric electric field at sea level, especially in industrial areas of highly variable atmospheric pollution.
(Reference: http://amsglossary.allenpress.com/glossary/browse?s=c&p=68)

**Cold front:** The term "cold front" is one of meteorology's most misused terms. Many people say "cold front" when they are really talking about the mass of cold air that moves in behind the front. In weather, all fronts are boundaries between masses of air with different densities, usually caused by temperature differences. A cold front is a warm-cold air boundary with the colder air replacing the warmer. While a winter cold front can bring frigid air, summer cold fronts often can more accurately be called "dry" fronts. As anyone who's ever suffered through a few days of hot, humid air anywhere east of the Rockies can tell you, cold fronts are welcome visitors because they often bring air that might be only a few degrees cooler, but much less humid. The weather map symbol for a cold front is a blue line with triangles pointing the direction the cold air is moving. As a cold front moves into an area, the heavier, cool air pushes under the lighter, warm air it's replacing. The warm air cools as it rises. If the rising air is humid enough, water vapor in it will condense into clouds and maybe precipitation. In the summer, an arriving cold front can trigger thunderstorms, sometimes severe thunderstorms with large hail, dangerous winds and even tornadoes. As a cold front arrives in a particular place, the barometric pressure will fall and then rise. Winds ahead of a cold front tend to be from a southerly direction while those behind the front - in the cooler air - tend to be northerly. In fact, weather stations use the shift from a southerly to a northerly wind direction as the indication that a cold front has passed the station.
(Reference: http://www.usatoday.com/weather/tg/wcfront/wcfront.htm.)

**Continental drift:** Geological theory stating that the relative positions of the continents on the earth’s surface have changed considerably through geologic time. Though first proposed by American geologist Frank Bursley Taylor in a lecture in 1908, the first detailed theory of continental drift was put forth by German meteorologist and geophysicist Alfred Wegener in 1912. On the basis of geology, biology, climatology, and the alignment of the continental shelf rather than the coastline, he believed that during the late Paleozoic and early Mesozoic eras, about 275 to 175 million years ago, all the continents were united into a vast supercontinent, which he called Pangaea. Later, Pangaea broke into two supercontinental masses - Laurasia to the north, and Gondwanaland to the south. The present continents began to split apart in the latter Mesozoic era about 100 million years ago, drifting to their present positions. As additional evidence Wegener cited the unusual presence of coal deposits in the South Polar regions, glacial features in present-day equatorial regions, and the jigsaw fit of the opposing Atlantic continental shelves. He also pointed out that a plastic layer in the earth’s interior must exist to accommodate vertical adjustments caused by the creation of new mountains and by the wearing down of old mountains by erosion. He postulated that the earth’s rotation caused horizontal adjustment of rock in this plastic layer, which caused the continents to drift. The frictional drag along the leading edges of the drifting continents results in mountain building. Wegener's theory stirred considerable controversy during the 1920s. South African geologist A. L. Dutoit, in 1921, strengthened the argument by adding more exacting details that correlated geological and paleontological similarities on both sides of the Atlantic. In 1928, Scottish geologist Arthur Holmes suggested that thermal convection in the mantle was the mechanism that drove the continental movements. American geologist David Griggs performed scale

model experiments to show the mantle movements. The theory of continental drift was not generally accepted, particularly by American geologists, until the 1950s and 60s, when a group of British geophysicists reported on magnetic studies of rocks from many places and from each major division of geologic time. They found that for each continent, the magnetic pole had apparently changed position through geologic time, forming a smooth curve, or pole path, particular to that continent. The pole paths for Europe and North America could be made to coincide by bringing the continents together. See plate tectonics; seafloor spreading.
(Reference: http://education.yahoo.com/reference/encyclopedia/entry?id=11506)

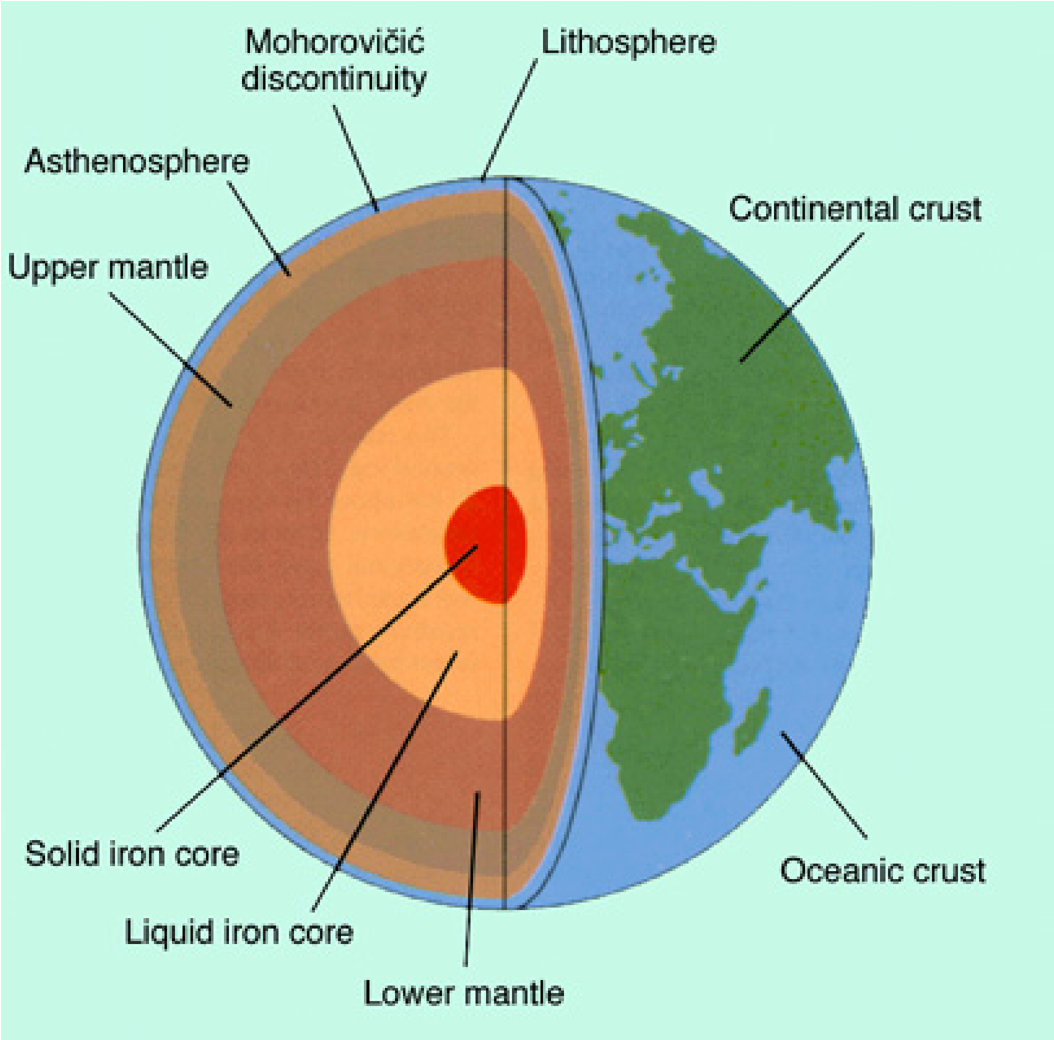
**Convection:** Convection functions because heated fluids, due to their lower density, rise and cooled fluids fall. A heated fluid will rise to the top of a column, radiate heat away and then fall to be re-heated, rise and so on. Gasses, like our atmosphere, are fluids, too. A packet of fluid can become trapped in this cycle. When it does, it becomes part of a convection cell.
(Reference: http://www.solarviews.com/eng/edu/convect.htm).

**Coordinate system:** (Also called reference frame.) Any scheme for the unique identification of each point of a given continuum. These may be points in space (Eulerian coordinates) or parcels of a moving fluid (Lagrangian coordinates). Newton's laws of motion do take different forms in different systems. The geometry of the system is a matter of convenience determined by the boundaries of the continuum or by other considerations (i.e., Cartesian coordinates, curvilinear coordinates).
(Reference: http://amsglossary.allenpress.com/glossary/search?id=coordinate-system1)

**Coriolis effect:** The Coriolis effect is an inertial force first described by Gaspard-Gustave Coriolis, a French scientist, in 1835. When the equations of motion are formulated in a rotating coordinate system a term arises which looks like a force, called the *Coriolis force*. This term means that the force will be proportional to the velocity of the object and the rotation of the coordinate system. The force will be in a direction perpendicular to the velocity (and thus does no work). If an object is traveling on earth in the northern hemisphere, the Coriolis force will deflect the object to the right. In the southern hemisphere the reverse is true, while at the equator the horizontal component of the force is zero for horizontal motions. The Coriolis force plays a strong role in weather patterns, where it affects prevailing winds and the rotation of storms, as well as in the direction of ocean currents. Above the atmospheric boundary layer, friction plays a relatively minor role, as air parcels move mostly parallel to each other. Here, an approximate balance between pressure gradient force and Coriolis force exists, causing the geostrophic wind, which is the wind effected by these two forces only, to blow along isobars (along lines of constant geopotential height, to be precise). Thus a northern hemispheric low pressure system rotates in a counterclockwise direction, while northern hemispheric high pressure systems or cyclones on the southern hemisphere rotate in a clockwise manner.
(Reference: http://www.free-definition.com/Coriolis-effect.html.)

**Craton:** A stable area of continental crust that has not undergone much plate tectonic or orogenic activity (see orogeny) for a long period. A craton includes a crystalline basement of commonly Precambrian rock called a shield, and a platform in which flat-lying or nearby flat-lying sediments or sedimentary rock surround the shield. A commonly cited example of a craton is the Canadian Shield.
(Reference: http://www.glossary.oilfield.slb.com/Display.cfm?Term=craton)

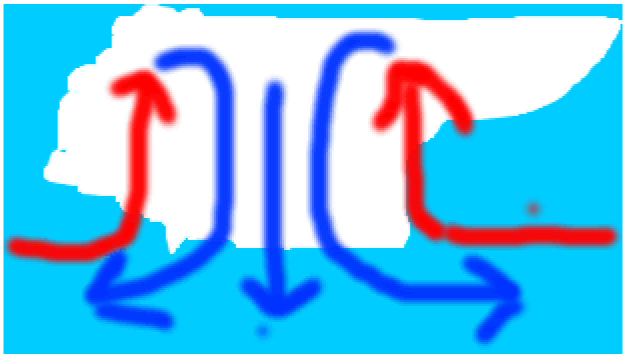
**Crust:** The thin, outermost shell of the earth that is typically 5 km to 75 km (3 to 47 miles) thick. The continental crust comprises rocks similar in composition to granite and basalt (i.e., quartz, feldspar, biotite, amphibole and pyroxene) whereas the composition of oceanic crust is basaltic (pyroxene and feldspar). The crust overlies the more dense rock of the mantle, which consists of rocks composed of minerals like pyroxene and olivine, and the iron and nickel core of the earth. The Mohorovicic discontinuity abruptly separates the crust from the mantle; the velocity of compressional waves is significantly higher below the discontinuity. The crust, mantle and core of the earth are distinguished from the lithosphere and asthenosphere on the basis of their composition and not their mechanical behavior.



(Reference: http://www.glossary.oilfield.slb.com/Display.cfm?Term=crust)

**Cb cloud:** Cumulonimbus cloud. Anvil shaped but not always. Severe ice, severe turbulence, lightning, heavy rain or hailstones, windshear; the Cb cloud is normally associated with the cold front. However on hot days an unstable atmosphere can trigger one of these clouds off on its own. The highest risk time is normally between midday and 3:00 PM. These clouds represent every bad weather thing you can think of. The clouds can rise to well above the cruise heights of most aircraft depending how close they are to the Equator. Modern airliners can pick these clouds up on weather radar to a range of 300 miles (480 km). Pilots will try and get Air Traffic Control Clearance to pass one of these clouds on the upwind side by at least twenty miles. If this cannot be arranged the pilot will put the seat belt sign on and slow the aircraft and on some aircraft can adjust the autopilot to relax the autopilot stiff resistance to movement. They will then have to just ride the bumps in the cloud. There have been many accidents as a result of these clouds around airports at the time of arrival. Often heavy showers of rain sleet or snow will fall.

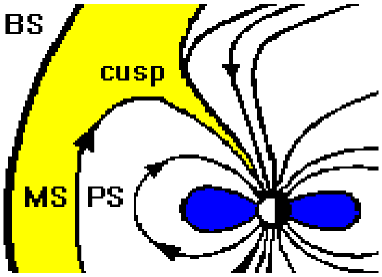
Hailstones also. The figure below shows the wind flow from one of these clouds. The red lines show warm air being sucked into the cloud and rising. As a result of that, cold air rushes down and out to replace it. Imagine now an aircraft flying from left to right. The pilot will have a tailwind then a headwind then air which could force straight down at a terrific speed (know as a microburst) then a tailwind then a headwind again. All this is in a short time over a short distance with hail rain sleet slow and poor visibility. Sometimes this cloud can hide itself in with other clouds. This is known as an embedded thunderstorm. It can be very difficult to see in this case. Sometimes a whole group of these clouds can form in an area.



The life of a Cb cloud is about 40 minutes normally. Pilots should consider holding off at an airport if one of these clouds is in the vicinity of the airport. Lightning and hailstones can come from these clouds. The cloud starts its life as a towering cumulus convection cloud but may continue to rise into a cumulonimbus cloud. There is also ice in the clouds. Eventually the cold air forced out cools the surface air and the cloud collapses into Stratus clouds. The Cb cloud may have some rolling cumulus clouds near it as well. Rain is normally the heaviest in the first 5 minutes.
(Reference: http://www.avsim.com/geoffschool/CBclouds.htm)

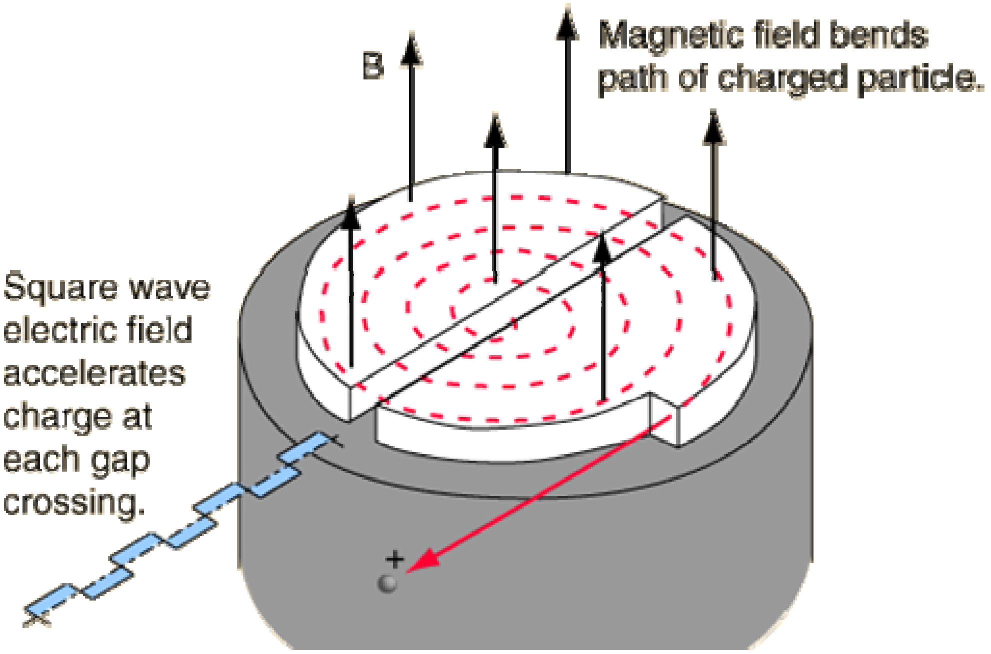
**Current:** 1. Any movement of material in space. 2. Any movement of electric charge in space, by virtue of which a net transport of charge occurs as, for example (in atmospheric electricity), in a conduction current, convection current, or precipitation current.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=current1)

**Cusp:** The magnetic field lines of the earth can be divided into two parts according to their location on the sunward or tailward side of the planet. Between these two parts on both hemispheres are funnel-shaped areas with near zero magnetic field magnitude called the polar cusps (or just cusps). They provide a direct entry for the magnetosheath plasma into the magnetosphere. (In the figure below BS = bow shock; MS = magnetosphere; and PS = plasmasphere.)

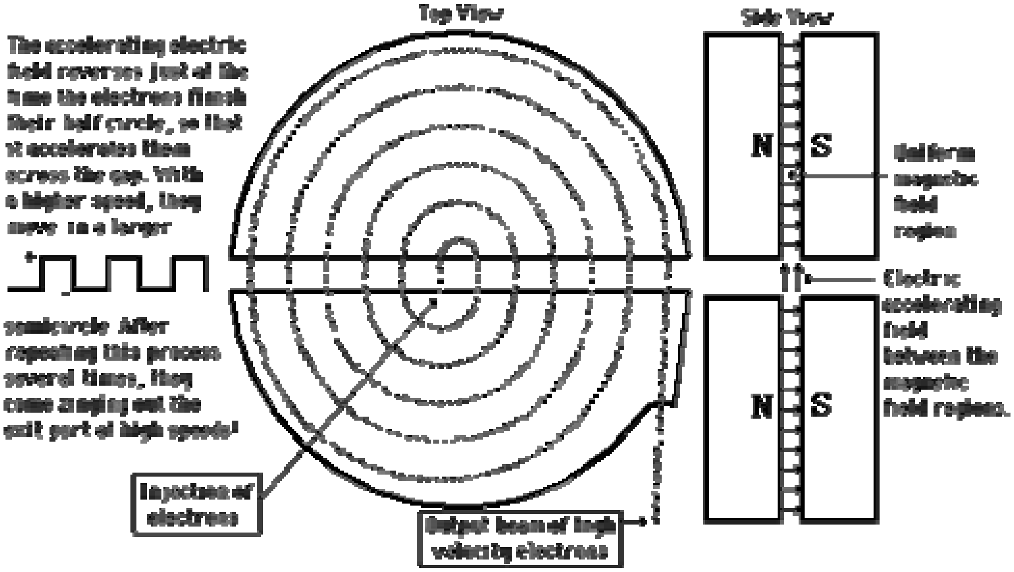


(Reference:  http://www.oulu.fi/~spaceweb/textbook/cusp.html.)

**Cyclotron:** The cyclotron was one of the earliest types of particle accelerators, and is still used as the first stage of some large multi-stage particle accelerators. It makes use of the magnetic force on a moving charge to bend moving charges into a semicircular path between accelerations by an applied electric field. The applied electric field accelerates electrons between the "dees" of the magnetic field region. The field is reversed at the cyclotron frequency to accelerate the electrons back across the gap.



When the cyclotron principle is used to accelerate electrons, it has been historically called a betatron. The cyclotron principle as applied to electrons is illustrated below.



(Reference: http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/cyclot.html)

**Cyclotron frequency:** The magnetic force $\mathbf{F_B}$ for charge particle (with charge q) moving with velocity $\mathbf{v}$ in a magnetic field $\mathbf{B}$ is $\mathbf{F_B} = q(\mathbf{v}\times\mathbf{B})$. The magnetic force is perpendicular to both the velocity $\mathbf{v}$ and magnetic field $\mathbf{B}$. The power done by the magnetic force $P = F \bullet v = 0$. So the magnetic force will not change the kinetic energy of the charge particle, it only changes the direction of the velocity for the charge particle. If the velocity is in the same direction of the magnetic field, then there is no magnetic force acting on the charge particle. For charge particle moving in a uniform magnetic field $\mathbf{B_o}$,the velocity can be represented as $\mathbf{v} = \mathbf{v}_\upsilon + \mathbf{v}_\tau$, $\mathbf{v}_\tau$ is a component of velocity along $\mathbf{B}$, which will not change. The particle advances along $\mathbf{v}_\tau$ while it moves in a circle in the plane formed by $\mathbf{v}_\upsilon$ and $\mathbf{B_o}$. The resulting trajectory forms a spiral with its axis along $\mathbf{B_o}$, $q(\mathbf{v}_\upsilon\times\mathbf{B}) = m\, v_\upsilon^2/R$, where R is the radius. So we have momentum $p_\upsilon = m\, v_\upsilon = qBR$, and the angular velocity of the circular motion $\omega = v_\upsilon/R = qB/m$, which is independent of the velocity of the charge particle! ($f = \omega/2\pi$ is the cyclotron frequency)
The constancy of the cyclotron frequency led to a device called cyclotron.
(Reference: http://www.phy.ntnu.edu.tw/java/cyclotron/cyclotron.html)

**Dart leader:** (Also called continuous leader.) The leader which, after the first stroke, typically initiates each succeeding stroke of a multiple-stroke flash lightning. (The first stroke is initiated by a stepped leader.) The dart leader derives its name from its appearance on photographs taken with streak cameras. The dart leader's brightest luminosity is at its tip which is tens of meters in length, propagating downward at about 107 m/s. In contrast to stepped leaders, dart leaders do not typically exhibit branching because the previously established channel's low gas density and residual ionization provide a more favorable path for this leader than do any alternative ones.
From: Chalmers, J. A., 1957: Atmospheric Electricity, p. 239.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=dart-leader1)

**Dipole:** 1. Without qualification usually means electric dipole, a system composed of two charges of equal and opposite sign separated by a distance. A magnetic dipole is an electric current loop enclosing a finite area in a plane. See dipole moment. 2. Same as dipole antenna.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=dipole1)

**Dipole antenna**: A type of antenna for transmitting or receiving electromagnetic radiation, most often in the radio frequency band. The term dipole antenna has no necessary connection with dipole radiation in the sense usually meant in electromagnetic theory (the lowest-order term of electromagnetic radiation) but arises from configuration: A dipole antenna is essentially two thin (diameter much less than length) conductors or poles separated by a gap by means of which an oscillating electric current is fed into (or out of) them. If the total length of the two poles is much less than the wavelength of their radiation, the dipole antenna is sometimes called a short dipole, the source of the term dipole radiation (radiation from an ideal oscillating dipole of negligible extent). Sometimes dipole antenna means an antenna with a length of half the wavelength, but a more precise term is half-wave dipole. The defining characteristic of a dipole antenna is its two identical components, not its length.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=dipole-antenna1)

**Dipole moment:** Without qualification usually means electric dipole moment, the product of charge and separation distance of an (electric) dipole. Dipole moment is a vector, its direction determined by the position vector from the negative to the positive charge. Dipole moments (usually of molecules) are classified as permanent (the centers of positive and negative charge do not coincide even when subjected to no external field) and induced (charge separation is a consequence of an external field acting in opposite directions on positive and negative charges). Water is often given as the prime example of a

molecule with a permanent dipole moment. The magnetic dipole moment of a magnetic dipole is the product of the electric current in the loop and the area it encloses. Magnetic dipole moment also is a vector, its direction determined by the normal to the plane of the current loop, the sense of this normal specified by the right-hand rule.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=dipole-moment1)

**Discharge:** 1. See electric discharge. 2. The volumetric rate of flow or volume flux.

**Discrete aurora:** Discrete auroras are the most intense auroral types where field-aligned acceleration plays an important role, forming the so-called inverted-V precipitation (see field-aligned acceleration for an explanation of inverted-V precipitation).
(Reference: http://www.oulu.fi/~spaceweb/textbook/aurora/discrete.html.)

**Drift mechanisms:** In the presence of only uniform magnetic field **B** (a bolded quantity is a vector), the motion of a charged particle can be described with gyration about the guiding center and motion along the field line. This motion gets more complicated when we add, in the first place, uniform external forces like electric fields or gravitational forces. Even more complicated situations arise with non-uniform magnetic field configurations, or time varying electric fields. We talk about the drift of the particle (guiding center motion).

Uniform external forces

In the presence of both magnetic and electric fields, the equation of motion for charged particle (velocity **v**, time t, mass m, charge q, electric field **E**) is m d**v**/dt = q (**E** + **v** x **B**). This leads to plasma drift (or **E** x **B** drift, as it is also called) with velocity **v** = **E** x **B** / B^2 (B^2 means magnitude of B square). Because **v** is independent of the mass and sign of the charge, it is the same for negatively and positively charged particles, and does not create electric current. However, in a plasma where collisions between charged and neutral particles are important, an important current called the Hall current (see Hall effect) is created because ions move slower (ion - neutral collision frequency is greater than electron - neutral collision frequency). To give an example, the pulsating auroral patches are often seen to drift under the **E** x **B** influence. The situation is not much different in the case of gravitational force **g**, for which we get **v** = (m/q) **g** x **B** / B^2. However, this drift is opposite for particles of opposite charge, and a current is created even in a collisionless plasma.

Nonuniform magnetic fields

In the case of non-uniform magnetic fields the gradient and curvature of the magnetic field **B** create drifts that add up and are in opposite directions for particles of opposite signs (forming currents). Both drifts are perpendicular to **B**, and in addition the gradient drift is perpendicular to the field gradient, and the curvature drift to the plane in which the magnetic field is curved. Also, the gradient and curvature drifts are proportional to the perpendicular and parallel energies of the particle, respectively. The east to west directed ring current in the earth 's magnetosphere is created by the combined curvature and gradient drift. Closely related to the gradient drift is the fact that, when magnetic field has longitudinal variation (i.e., convergence or divergence of the field lines), both positively and negatively charged particles are accelerated in the direction of decreasing magnetic field. This results to what is called the magnetic mirror effect, where particles are reflected from the region of converging magnetic field lines. This relates also to the first adiabatic invariancy, i.e., that the orbital magnetic moment is constant.

Time-varying electric fields

The effect of a slowly varying electric field on a charged particle drift is the addition of polarization drift velocity, **v** = m (d**E(perp)**/dt) / (qB^2), where perp indicates the perpendicular component of the electric field **E** to the magnetic field **B**. Since this drift is in opposite direction for charges of opposite sign, a net polarization current is produced. When the frequency of the changing electric field is the same as the particle's cyclotron frequency, a cyclotron resonance is created. This leads to increase in the particle speed and, due to collisions between particles, to radio frequency heating of the plasma. (Reference: http://www.oulu.fi/~spaceweb/textbook/drift.html.)

**Earth:** Earth in geology and astronomy, fifth largest planet of the solar system and the only planet definitely known to support life. Gravitational forces have molded the earth, like all celestial bodies, into a spherical shape. However, the earth is not an exact sphere, being slightly flattened at the poles and bulging at the equator. The equatorial diameter is 7,926 miles (12,760 km) and the polar diameter 7,900 miles (12,720 km); the circumference at the equator is 24,830 miles (40,000 km). The surface of the earth is divided into dry land and oceans, the dry land occupying 57.5 million sq miles (148.9 million sq km), and the oceans 139.5 million sq miles (361.3 million sq km). The earth is surrounded by an envelope of gases called the atmosphere, of which the greater part is nitrogen and oxygen.

The Geologic Earth

Knowledge of the earth's interior has been gathered by three methods: by the analysis of earthquake waves passing through the earth (see seismology), by analogy with the composition of meteorites, and by consideration of the earth's size, shape, and density. Research by these methods indicates that the earth has a zoned interior, consisting of concentric shells differing from one another by size, chemical makeup, and density (see definition of crust and picture therein). The earth is undoubtedly much denser near the center than it is at the surface, because the average density of rocks near the surface is 2.8 g/cc, while the average density of the entire earth is 5.5 g/cc.

The Earth's Crust and the Moho

The outer shell, or crust, varies from 5 to 25 mi (8 to 40 km) in thickness, and consists of the continents and ocean basins at the surface. The continents are composed of rock types collectively called sial, a classification based on their densities and composition. Beneath the ocean basins and the sial of continents lie denser rock types called sima. The sial and sima together form the crust, beneath which lies a shell called the mantle. The boundary between the crust and the mantle is marked by a sharp alteration in the velocity of earthquake waves passing through that region. This boundary layer is called the Mohorovičić discontinuity, or Moho.

The Earth's Mantle

Extending to a depth of 1,800 miles (2,900 km), the mantle probably consists of very dense (average 3.9) rock rich in iron and magnesium minerals. Although temperatures increase with depth, the melting point of the rock is not reached because the melting temperature is raised by the great confining pressure. At depths between 60 mi and 125 miles (100 and 200 km) in the mantle, a plastic zone, called the asthenosphere, is found to occur. Presumably the rocks in this region are very close to melting, and the zone represents a fundamental boundary between the moving crustal plates of the earth's surface and the interior regions. The molten magma that intrudes upward into crustal rocks or issues from a volcano in the form of lava may owe its origin to radioactive heating or to the relief of pressure in the lower crust and upper mantle caused by earthquake faulting of the overlying crustal rock. Similarly, it is thought that the heat energy released in the upper part of the mantle has broken the earth's crust into vast plates that slide around on the plastic zone, setting up stresses along the plate margins that result in the formation of folds and faults (see plate tectonics).

The Earth's Core

Thought to be composed of iron and nickel, the dense (11.0) core of the earth lies below the mantle. The abrupt disappearance of direct compressional earthquake waves, which cannot travel through liquids, at depths below 1,800 miles (2,900 km) indicates that the outer 1,380 miles (2,200 km) of the core are molten. It is thought, however, that the inner 780 miles (1,260 km) of the core are solid. The outer core is thought to be the source of the earth's magnetic field: In the "dynamo theory" advanced by W. M. Elasser and E. Bullard, tidal energy or heat is converted to mechanical energy in the form of currents in the liquid core; this mechanical energy is then converted to electromagnetic energy, which we see as the magnetic field.

The Astronomical Earth

The earth is the third planet in order from the sun, only Mercury and Venus being nearer; the mean distance from the earth to the sun is 93 million miles (150 million km).

Rotation and Revolution

The earth rotates from west to east about a line (its axis) that is perpendicular to the plane of the equator and passes through the center of the earth, terminating at the north and south geographical poles. The period of one complete rotation is a day; the rotation of the earth is responsible for the alternate periods of light and darkness (day and night). The earth revolves about the sun once in a period of a little more than 3651⁄4 days (a year). The path of this revolution, the earth's orbit, is an ellipse rather than a circle, and the earth is consequently nearer to the sun in January than it is in July; the difference between its maximum and minimum distances from the sun is 3 million miles (4.8 million km). This difference is not great enough to affect climate on the earth.

The Change in Seasons

The change in seasons is caused by the tilt of the earth's axis to the plane of its orbit, making an angle of 66.5°. When the northern end of the earth's axis is tilted toward the sun, the most direct rays of sunlight fall in the Northern Hemisphere. This causes its summer season. At the same time the Southern Hemisphere experiences winter since it is then receiving indirect rays. Halfway between, in spring and in autumn, there is a time (see equinox) when all parts of the earth have equal day and night. When the northern end of the earth's axis is tilted away from the sun, the least direct sunlight falls on the Northern Hemisphere. This causes its winter season.

The Origin of the Earth

The earth is estimated to be 4.5 billion to 5 billion years old, based on radioactive dating of lunar rocks and meteorites, which are thought to have formed at the same time. The origin of the earth continues to be controversial. Among the theories as to its origin, the most prominent are gravitational condensation hypotheses, which suggest that the entire solar system was formed at one time in a single series of processes resulting in the accumulation of diffuse interstellar gases and dust into a solar system of discrete bodies. Older and now generally discredited theories invoked extraordinary events, such as the gravitational disruption of a star passing close to the sun or the explosion of a companion star to the sun. See crust for a representation of the earth.
(Reference: http://education.yahoo.com/reference/encyclopedia/entry?id=14723)

**El Niño/La Niña:** El Niño episodes reflect periods of exceptionally warm sea surface temperatures across the eastern tropical Pacific. La Niña episodes represent periods of below-average sea-surface temperatures across the eastern tropical Pacific. During a strong El Niño ocean temperatures can average 2°C – 3.5°C (3.6°F – 6.3°F) above normal between the date line and the west coast of South America. These areas of exceptionally warm waters coincide with the regions of above-average tropical rainfall. During La Niña temperatures average 1°C - 3°C (1.8°F – 5.4°F) below normal between the date line and the west coast of South America. This large region of below-average temperatures coincides with the area of well below-average tropical rainfall. For both El Niño and La Niña the tropical rainfall, wind, and air pressure patterns over the equatorial Pacific Ocean are most strongly linked to the underlying sea-surface temperatures, and vice versa, during December-April. During this period the El Niño and La Niña conditions are typically strongest, and have the strongest impacts on U.S. weather patterns. El Niño and La Niña episodes typically last approximately 9-12 months. They often begin to form during June-August, reach peak strength during December-April, and then decay during May-July of the next year. However, some prolonged episodes have lasted 2 years and even as long as 3-4 years. While their periodicity can be quite irregular, El Niño and La Niña occurs every 3-5 years on average.
(Reference: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/ensocycle.html.)

**Electric charge:** A fundamental property of matter. This property exhibits two states, positive and negative, that result in the action of electric forces in the presence of an electric field.
These two states were identified and named by Benjamin Franklin. The positive charge on the proton and the negative charge on the electron represent the fundamental charge, $1.6 \times 10^{-19}$ coulomb (C).
(Reference: http://amsglossary.allenpress.com/glossary/search?id=electric-charge1)

**Electric discharge:** (Or, simply, discharge; also gaseous electric discharge, gaseous discharge.) The flow of electricity through a gas, resulting in the emission of radiation that is characteristic of the gas and of the intensity of the current.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=electric-discharge1)

**Electric field:** 1. A vector field, usually denoted by **E**, defined as follows: at a given time and at each point in space the force experienced by a positive charge (sometimes called a test charge) at that point divided by the magnitude of the charge, taken to be sufficiently small that it does not affect the positions and velocities of all other charges. The set of all vectors thus obtained is the electric field, although this term is often used for its value at any given point. The magnitude of the vector is the electric field intensity and the direction of the vector is parallel to the lines of force. 2. Same as electric field strength.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=electric-field1)

**Electrojet:** The term 'auroral electrojet' is the name given to the large horizontal currents that flow in the D and E regions of the ionosphere (see ionosphere). Although horizontal ionospheric currents can be expected to flow at any latitude where horizontal ionospheric electric fields are present, the auroral electrojet currents are remarkable for their strength and persistence. There are two main factors in the production of the electrojet. First of all, the conductivity of the auroral ionosphere is generally larger than that at lower latitudes. Secondly, the horizontal electric field in the auroral ionosphere is also larger than that at lower latitudes. Since the strength of the current flow is directly proportional to the vector product of the conductivity and the horizontal electric field, the auroral electrojet currents are generally larger compared to those at lower latitudes. During magnetically quiet periods, the electrojet is generally confined to the auroral oval. However during disturbed periods, the electrojet increases in strength and expands to both higher and lower latitudes. This expansion results from two factors, enhanced particle precipitation and enhanced ionospheric electric fields.
(Reference: http://www-star.stanford.edu/~vlf/ejet/electrojet.html.)

**Electromagnetic wave:** An oscillation of the electric or magnetic field associated with the propagation of electromagnetic radiation. Electromagnetic waves are characterized by their wavelength or wavenumber, amplitude, and polarization characteristics. They propagate at the speed of light.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=electromagnetic-wave1)

**Electromagnetic radiation:** Energy propagated in the form of an advancing electric and magnetic field disturbance. The term radiation, alone, is commonly used for this type of energy, although it actually has a broader meaning. In the classical wave theory of light (or electromagnetic theory) the propagation is thought of as a continuous wavelike disturbance of the electric and magnetic fields, which oscillate in planes orthogonal to each other and to the direction of propagation. The quantum theory of electromagnetic radiation adds the perspective that these disturbances also have particle-like attributes, being quantized into photons of minimum energy that have finite momentum. The observable properties and physical effects of various portions of the electromagnetic spectrum are of considerable importance in meteorology.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=electromagnetic-radiation1)

**Electromotive force (emf):** The energy per unit charge that is converted reversibly from chemical, mechanical, or other forms of energy into electrical energy in a battery or dynamo.
(Reference: http://www.thefreedictionary.com/electromotive%20force)

**Exosphere:** The exosphere is the uppermost layer of the atmosphere. On earth, its lower boundary is estimated at 500 km to 1000 km ((311 miles to 621 miles) above the earth's surface, and its upper boundary at about 10,000 km (6,200 miles). It is only from the exosphere that atmospheric gases can, to any appreciable extent, escape into outer space.
(Reference: http://www.free-definition.com/Exosphere.html.)

**Field:** In its restricted physical sense, any physical quantity that varies in three-dimensional space (and possibly time), usually continuously except possibly on surfaces or curves. Field quantities often satisfy partial differential equations. An example of a scalar field is the temperature T(x, y, z, t) at time t at each point (x, y, z) of a solid body; an example of a vector field is the (local) velocity field **v**(x, y, z, t) in a fluid, the separate parts of which are in motion relative to each other. The continuity of these fields is a mathematical fiction, obtained by averaging over volumes containing many atoms or molecules but still small on a macroscopic scale.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=field1)

**Field-aligned acceleration:** Observations of auroral precipitation characteristics (and the resulting ionospheric ionization profiles) have shown that, within discrete auroras, field-aligned acceleration of the precipitating electrons plays an important role (inverted-V electron precipitation). It seems likely that field-aligned potential drops (upward directed electric fields) are formed to create this effect, although different wave-related schemes have also been suggested. The problem is that it is not clear how the necessary magnetic field-aligned electric fields are supported in the magnetospheric plasma.
(Reference: http://www.oulu.fi/~spaceweb/textbook/potential_drops.html.)

**Field-aligned currents (FAC):** Field-Aligned currents are transient currents which short-circuit through a planet's ionosphere (which is a conducting medium), and which are part of generating the aurora.
(Reference: http://www.windows.ucar.edu/tour/link=/glossary/current_systems.html&edu=high)
Field-aligned currents (FAC, also called the Birkeland currents) are essential to the linkage between the solar wind - magnetosphere system and the ionosphere. The main large scale FAC systems are the Region 1 and 2 (R1 and R2) currents.

*Region 1 (R1) currents:*

- Inner ring driving the R1-R2 system
- Directed into the ionosphere in the morning hemisphere
- Directed out of the ionosphere in the evening hemisphere
  - Relates to the electron precipitation in the region of discrete auroras
- Expands to lower latitudes with increasing activity (see also auroral ovals)
- Gets weaker during weak activity (northward IMF, i.e., $NB_{z;}$ where $B_z$ = the z component of the interplanetary magnetic field) )
- Maximises between 0800 and 1000 MLT (Magnetic Local Time) in the morning side and between 1400 and 1600 MLT in the afternoon side
- Current increases as the electric field associated with the solar wind-IMF increases (but is non-zero even during zero electric field, just like the polar cap potential difference)

*Region 2 (R2) currents:*

- Outer ring following the R1 system
- Current directions opposite to the Region 1 system

- Responds to the activity level as Region 1 current ring

*Mantle-NBZ currents*

- Poleward of the R1 near local noon (see cusp)
- Current directions opposite to the adjacent R1 currents
- Strong IMF $B_y$ effect (IMF $B_y$ = the y component of the interplanetary magnetic field): for $B_y > 0$ predominantly upward in the northern hemisphere and downward in the southern, and the other way round for $B_y < 0$
- Strong IMF $B_z$ effect
  - $B_z < 0$: mantle (previously called the cusp) currents
    - Well localized, weak currents
  - $B_z > 0$: $NB_z$ currents
    - Expand and become as strong as the weakened R1-R2 currents

(Reference: http://www.oulu.fi/~spaceweb/textbook/fac.html.)

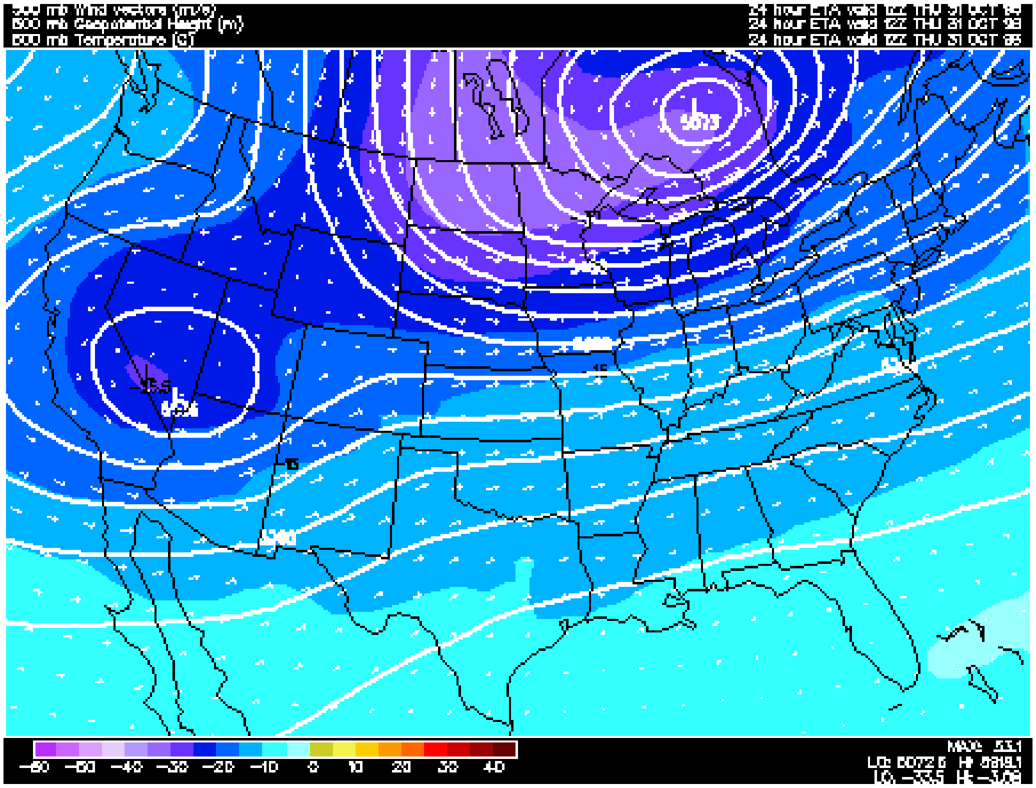
**Forbush decrease:** A decrease in cosmic ray intensity during active Sun (the Sun during its 11-year cycle of activity when spots, flares, prominences, and variations in radio frequency radiation are at a maximum). Discovered by Forbush in 1954.
(Reference: http://www.site.uottawa.ca:4321/astronomy/index.html#Forbushdecrease)

**Forked lightning:** The common form of cloud-to-ground discharge always visually present to a greater or lesser degree that exhibits downward-directed branches from the main lightning channel. In general, of the many branches of the stepped leader, only one is connected to the ground, defining the primary, bright return stroke path; the other incomplete channels decay after the ascent of the first return stroke. Compare streak lightning, zigzag lightning.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=forked-lightning1)

**Gamma ray:** (Or γ-ray, γ ray, γ radiation, gamma radiation.) Electromagnetic radiation originating from transitions between energy levels of atomic nuclei. A nucleus formed as a consequence of beta or alpha emission sometimes exists briefly in an excited energy level and makes a transition to a lower energy level accompanied by emission of a gamma ray photon with energy equal to the difference between the energies of the initial and final levels. Gamma ray energies from radioactive decay lie in the approximate range 10 keV–6 MeV. Gamma rays are also emitted in nuclear reactions. The boundary between x-rays and gamma rays is fuzzy, the latter term being most often used for electromagnetic radiation of nuclear origin.
From: Boorse, H. A., and L. Motz, 1966: The World of the Atom, Vol. I, 446–448.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=gamma-ray1)

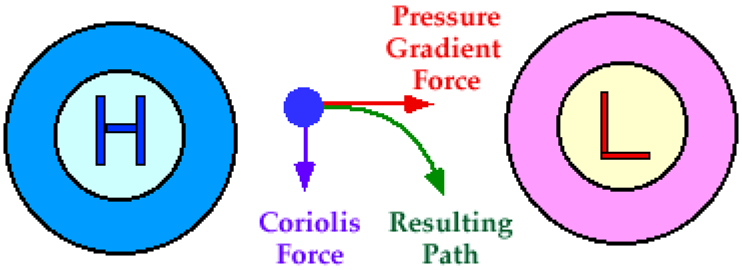
**Geomagnetic field:** The earth's magnetic field is both expansive and complicated. It is generated by electric currents that are deep within the earth and high above the surface. All of these currents contribute to the total geomagnetic field. In some ways, one can consider the earth's magnetic field, measured at a particular instance and at a particular location, to be the superposition of symptoms of a myriad of physical processes occurring everywhere else in the world. The challenge is to untangle the rich information content of the magnetic field so that we can better understand our planet and the surrounding space environment in which it resides.
(Reference: see #5 in the Reference section.)

**Geopotential height:** Height of a given pressure. Geopotential height approximates the actual height of a pressure surface above mean sea-level. Therefore, a geopotential height observation represents the height of the pressure surface on which the observation was taken. A line drawn on a weather map connecting points of equal height (in meters) is called a height contour. That means, at every point along a given contour, the values of geopotential height are the same. An image depicting the geopotential height field is given below.

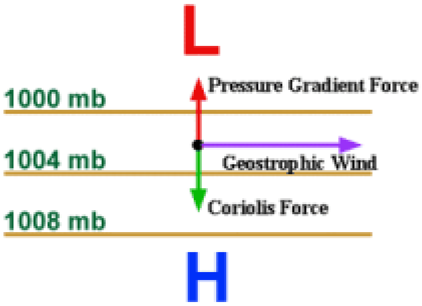


Height contours are represented by the solid lines. The small numbers along the contours are labels which identify the value of a particular height contour (for example 5640 meters, 5580 meters, etc.). (Reference: http://ww2010.atmos.uiuc.edu/(Gh)/wwhlpr/geopotential_height.rxml?hret=/guides/maps/upa/hght.rxml)

**Geostrophic wind:** Winds balanced by the Coriolis and Pressure Gradient forces. An air parcel initially at rest will move from high pressure to low pressure because of the pressure gradient force (PGF). However, as that air parcel begins to move, it is deflected by the Coriolis force to the right in the northern hemisphere (to the left on the southern hemisphere). As the wind gains speed, the deflection increases until the Coriolis force equals the pressure gradient force. At this point, the wind will be blowing parallel to the isobars. When this happens, the wind is referred to as geostrophic.



The diagram below shows the two forces balancing to produce the geostrophic wind. Winds in nature are rarely exactly geostrophic, but to a good approximation, the winds in the upper troposphere can be close. This is because winds are only considered truly geostrophic when the isobars are straight and there are no other forces acting on it -- and these conditions just aren't found too often in nature.



(Reference: http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/fw/geos.rxml)

**Geotherm:** Or geothermal gradient, the change in temperature with increasing pressure (depth) in the earth.
(Reference: http://www.personal.umich.edu/~essene/508%20metamorphic%20petrology/508%20lectures/508.02%20%20definitions.doc)

**Graben:** Elongated, trenchlike, structural form bounded by parallel normal faults created when block that forms trench floor moves downward relative to blocks that form sides.
(Reference: Leet, L. Don. 1982. Physical Geology, 6th Edition. Englewood Cliffs, NJ: Prentice-Hall)

**Graupel:** Heavily rimed snow particles, often called snow pellets; often indistinguishable from very small soft hail except for the size convention that hail must have a diameter greater than 5 mm. Sometimes distinguished by shape into conical, hexagonal, and lump (irregular) graupel.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=graupel1)

**Greenwich Mean Time (GMT):** Greenwich, England has been the home of Greenwich Mean Time (GMT) since 1884. GMT is sometimes called Greenwich Meridian Time because it is measured from the Greenwich Meridian Line at the Royal Observatory in Greenwich, England.
(Reference: http://wwp.greenwichmeantime.com)

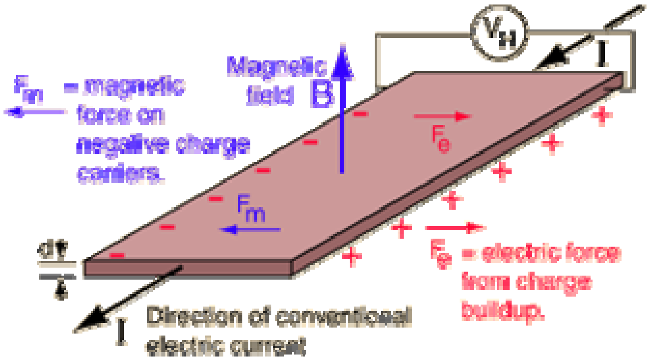
**Greenwich Meridian Line:** The Meridian Line is an imaginary line that runs from the North Pole to the South Pole. By international convention it runs through "the primary transit" instrument (main telescope) at the Royal Observatory in Greenwich. It is known at Zero Longitude and it is the line from which all other lines of longitude are measured. This includes the line that runs 180° away from Greenwich also known as the International Date Line.
(Reference: http://greenwichmeridian.com/line.htm)

**Ground-to-cloud discharge:** A lightning discharge in which the original leader process starts upward from some object on the ground; the opposite of the more common cloud-to-ground discharge. Ground-to-cloud discharges most frequently emanate from very tall structures that, being at the same potential as the earth, can exhibit the strong field intensities near their upper extremities necessary to initiate leaders.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=ground-to-cloud-discharge1)

**Gyrofrequency:** Angular frequency of gyration, cyclotron frequency, or Larmor frequency. The magnitude of the angular velocity of a charged particle gyrating around its guiding center, w = |q|B/m (in radians/s). The smaller the particle mass, the larger its gyrofrequency will be, and the higher the magnetic field, the higher the gyrofrequency, also. See also gyroradius and cyclotron frequency.
(Reference: http://www.oulu.fi/~spaceweb/textbook/basics.html#Gyrofrequency)

**Gyroradius:** Radius of gyration, or cyclotron radius. The radius of the circular orbit of a charged particle gyrating around its guiding center, r = v(perp)/w = mv(perp) /(|q|B). The smaller the particle mass, the smaller its gyroradius will be, and the higher the magnetic field, the smaller the gyroradius, also. See also gyrofrequency (w).
(Reference: http://www.oulu.fi/~spaceweb/textbook/basics.html#Gyrofrequency)

**Hall effect:** If an electric current flows through a conductor in a magnetic field, the magnetic field exerts a transverse force on the moving charge carriers which tends to push them to one side of the conductor. This is most evident in a thin flat conductor as illustrated. A buildup of charge at the sides of the conductors will balance this magnetic influence, producing a measurable voltage between the two sides of the conductor. The presence of this measurable transverse voltage is called the Hall effect after E. H. Hall who discovered it in 1879.



The Hall voltage is given by

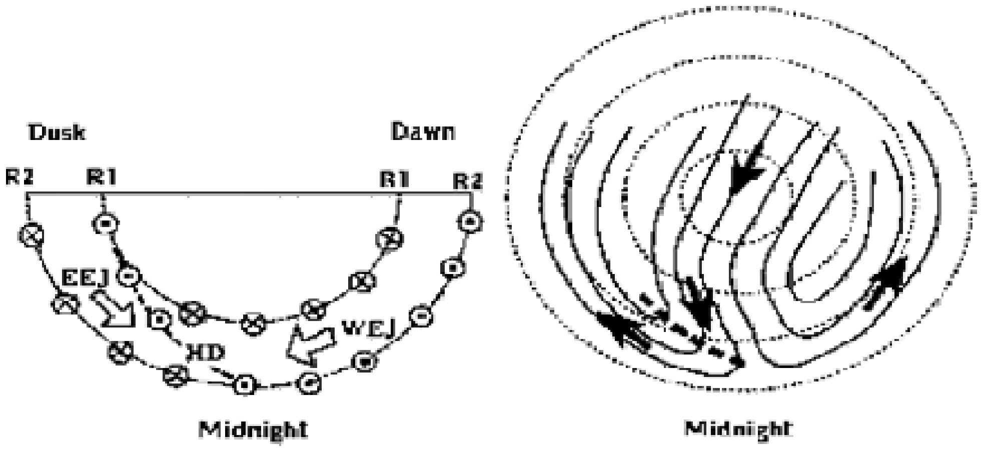
$$V_H = \frac{IB}{ned}$$

$n$ = density of mobile charges
$e$ = electron charge

The Hall effect can be used to measure magnetic fields with a Hall probe.

Note that the direction of the current I in the diagram is that of conventional current, so that the motion of electrons is in the opposite direction. That further confuses all the "right-hand rule" manipulations you have to go through to get the direction of the forces. The Hall current is the transverse motion of electrons that creates the Hall voltage.
(Reference: http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/hall.html)

**Harang discontinuity:** The Harang discontinuity (HD) is a region of sharp reversal of the evening sector (around 2200-2400 MLT or Magnetic Local Time) ionospheric convection electric field from the poleward field on the equatorward side of the auroral oval to an equatorward field on the poleward side of the oval. In terms of auroral electrojets the discontinuity corresponds to the shear zone where the eastward electrojet (EEJ), equatorward of the shear, and the westward electrojet (WEJ), poleward of the shear, meet. Strangely enough, the location of the discontinuity is little different depending on the way it is measured: the direct "electric" discontinuity is 1-2° poleward of the "magnetic" (electrojets as observed from ground) one.



Schematic picture of the Harang discontinuity (HD, dashed line). In the left panel the electrojets and large-scale FACs are shown, and in the right panel the arrows indicate the plasma flow directions. R1, R2 = Region 1 and 2 currents, EEJ, WEJ = eastward and westward electrojets (from Koskinen and Pulkkinen, 1995).

The longitudinal position of the Harang discontinuity is controlled by the interplanetary magnetic field (IMF). By component: increasing positive (negative) values displace it towards earlier (later) local times within the evening sector. HD is a often a source of strong FAC collocated with the nightside region 1 current system, which may be a result of a dawn-dusk pressure gradient in the central plasma sheet. The role of the Harang discontinuity in substorms is not yet properly established. Many events have shown how the substorm onset arc is located just equatorward of the "electric" HD. It should also have some relationship to ionospheric trough (see that term in this glossary).
(Reference: http://www.oulu.fi/~spaceweb/textbook/harang.html.)

**Igneous rock:** Rock that solidified from molten or partly molten material, for example, magma. Igneous rock is high in electrical resistivity and common over large portions of North America.
(Reference: see #7 in the Reference section.)

**Interplanetary magnetic field (IMF):** The magnetic field carried with the solar wind.
(Reference: http://space.about.com/od/glossaries/g/intplanmagfield.htm)

**Ionosphere:** In a region extending from a height of about 50 km (31 miles) to over 500 km (311 miles), some of the molecules of the atmosphere are ionized by radiation from the Sun to produce an ionized gas. This region is called the ionosphere. It is the ions that give their name to the ionosphere, but it is the much lighter and more freely moving electrons that are important in terms of high frequency (HF: 3 to 30 MHz) radio propagation. Note that many references to ionospheric communications speak of reflection of the wave. It is, however, a refraction process. Generally, the greater the number of electrons, the higher the frequencies that can be refracted from the ionosphere. During the day the ionosphere may have four regions present called the D, E, F1 and F2 regions. Their approximate height ranges are:

- D region 50 to 90 km (31 to 56 miles; weakly ionized and absorbs high-frequency radio waves);
- E region 90 to 150 km (56 to 93 miles; ions in this region are mainly $O_2^+$);
- F1 region 150 to 210 km (93 to 130 miles; ions are mainly $NO^+$);
- F2 region over 210 km (over 130 miles; ions are predominantly $O^+$).

There is also a part of the ionosphere called the topside that starts at the height of the maximum density of the F2 layer of the ionosphere and extends upward with decreasing density to a transition height where $O^+$ ions become less numerous than $H^+$ and $He^+$. The transition height varies but seldom drops below 500 km (311 miles) at night or 800 km (500 miles) in the daytime, although it may lie as high as 1100 km (684 miles). Above the transition height, the weak ionization has little influence on radio signals. During the daytime, sporadic E (see its definition) is sometimes observed in the E region, and at certain times during the solar cycle the F1 region may not be distinct from the F2 region but merge to form an F region. At night the D, E and F1 regions become very much depleted of free electrons, leaving only the F2 region available for communications; however it is not uncommon for sporadic E to occur at night. Only the E, F1, sporadic E when present, and F2 regions refract HF waves. The D region is important though, because while it does not refract HF radio waves, it does absorb or attenuate them. The lifetime of electrons is greatest in the F2 region which is one reason why it is present at night. Typical lifetimes of electrons in the E, F1 and F2 regions are 20 seconds, 1 minute and 20 minutes, respectively.

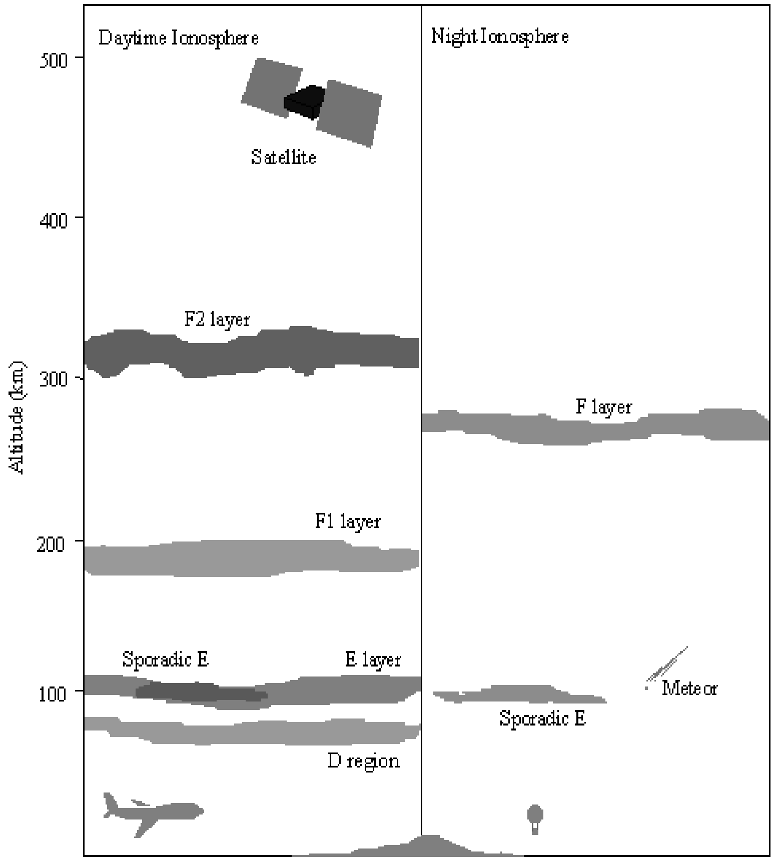


Figure 1. Day and night structure of the ionosphere.

Radiation from the Sun causes ionization in the ionosphere. Electrons are produced when this radiation collides with uncharged atoms and molecules, see Figure 2. Since this process requires solar radiation, production of electrons only occurs in the daylight hemisphere of the ionosphere.

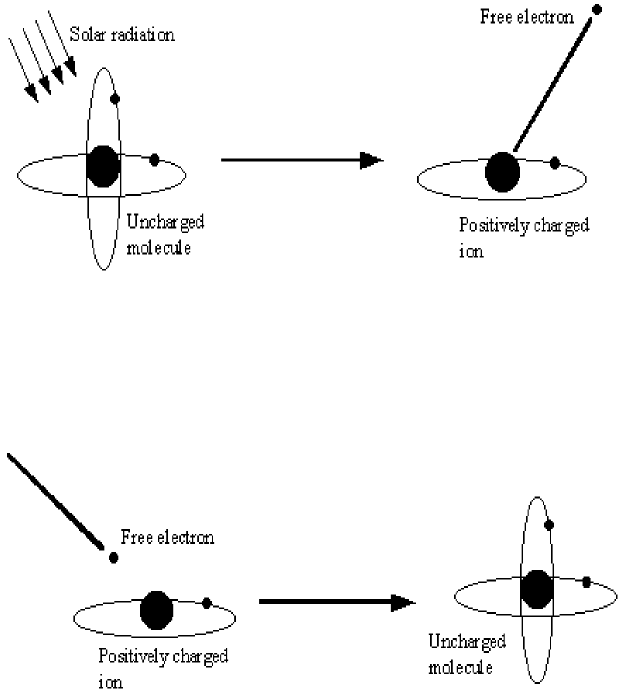


Figure 2. Production (top) and loss (bottom) of ions.

When a free electron combines with a charged ion a neutral particle is usually formed, Figure 2. Essentially, loss is the opposite process to production. Loss of electrons occurs continually, both day and night. The ionosphere is not a stable medium which allows the use of one frequency over the year, or even over 24 hours. The ionosphere varies with the solar cycle, the seasons, the global circuit and during any given day. So, an electromagnetic frequency which may provide successful propagation now, may not do so an hour later.

### *1.Variations due to the solar cycle*

The Sun goes through a periodic rise and fall in activity which affects HF communications; solar cycles vary in length from 9 to 14 years. At solar minimum, only the lower frequencies of the HF band will be supported by the ionosphere, while at solar maximum the higher frequencies will successfully propagate, see Figure 3. This is because there is more radiation being emitted from the Sun at solar maximum, producing more electrons in the ionosphere which allows the use of higher frequencies.

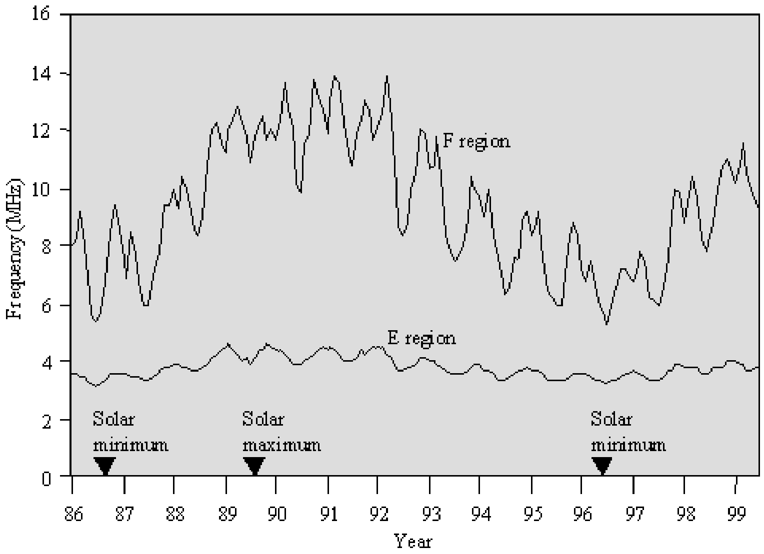


Figure 3. Solar cycle and seasonal dependence of E and F region frequencies for a near vertical incidence sky wave (NVIS) circuit in the southern hemisphere.

There are other consequences of the solar cycle. Around solar maximum there is a greater likelihood of large solar flares occurring. Flares are huge explosions on the Sun which emit radiation that ionizes the D region causing increased absorption of HF waves. Since the D region is present only during the day, only those communication paths that pass through daylight will be affected. The absorption of HF waves traveling via the ionosphere after a flare has occurred is called a short wave fade-out (see short wave fade-out). Fade-outs occur instantaneously and affect lower frequencies the most. Lower frequencies are also the last to recover. If it is suspected or confirmed that a fade-out has occurred, it may help to try using a higher frequency. However, if a flare is very large, the whole of the HF spectrum may be rendered unusable. The duration of fade-outs can vary between about 10 minutes to over an hour depending on the intensity and duration of the flare.

### *2. Seasonal variations*

E region frequencies are greater in summer than winter, see Figure 3. However, the variation in F region frequencies is more complicated. In both hemispheres, F region noon frequencies generally peak around the equinoxes (March and September). Around solar minimum the summer noon frequencies are, as expected, generally greater than those in winter, but around solar maximum, winter frequencies at certain locations, can be higher than those in summer. In addition, frequencies around the equinoxes (March and September) are higher than those in summer or winter for both solar maximum and minimum. The observation of noon, winter frequencies often being greater than those in summer is called the seasonal anomaly (this is not observed in Figure 3)

### 3 Variations with latitude

Figure 4 indicates the variations in E and F region frequencies at noon and midnight from the poles to the geomagnetic equator. During the day and with increasing latitude, solar radiation strikes the atmosphere more obliquely, so the intensity of radiation and the electron density production decreases towards the poles.

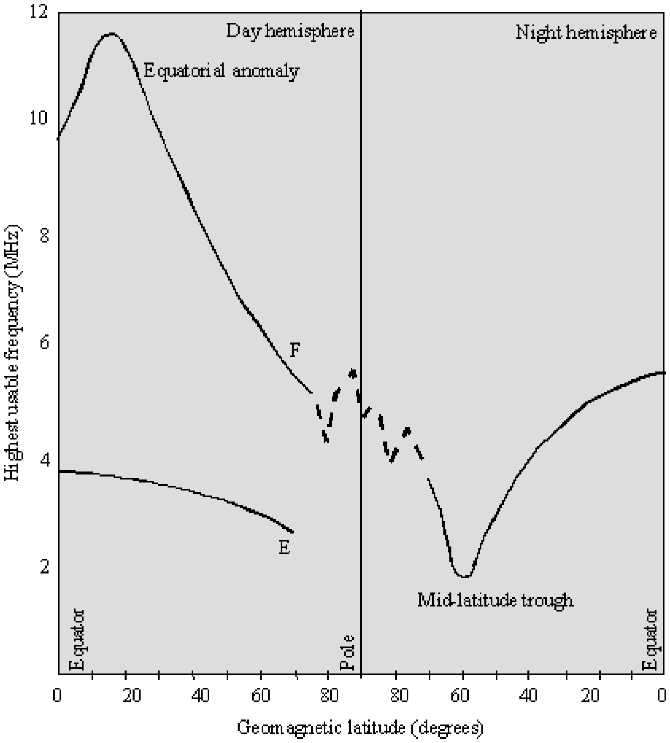


Figure 4. Representation of latitudinal variations.

Note in Figure 4 how the daytime F region frequencies peak not at the magnetic equator, but around 15 to 20 degrees north and south of it. This is called the equatorial anomaly. At night, frequencies reach a minimum around 60 degrees latitude north and south of the geomagnetic equator. This is called the mid-latitude trough. Large tilts can occur in the vicinity of these phenomena which may lead to variations in the range of sky waves that have reflection points nearby.

### 4. Diurnal variations

Operating frequencies are normally higher during the day and lower at night, see Figure 5. With dawn, solar radiation causes electrons to be produced in the ionosphere and frequencies increase reaching their maximum around noon. During the afternoon, frequencies begin decreasing due to electron loss and with evening, the D, E and F1 regions become insignificant. HF sky wave communication during the night is therefore by the F2 region and absorption of radio waves is lower because of the lack of the D region. Through the night, frequencies decrease reaching their minimum just before dawn.

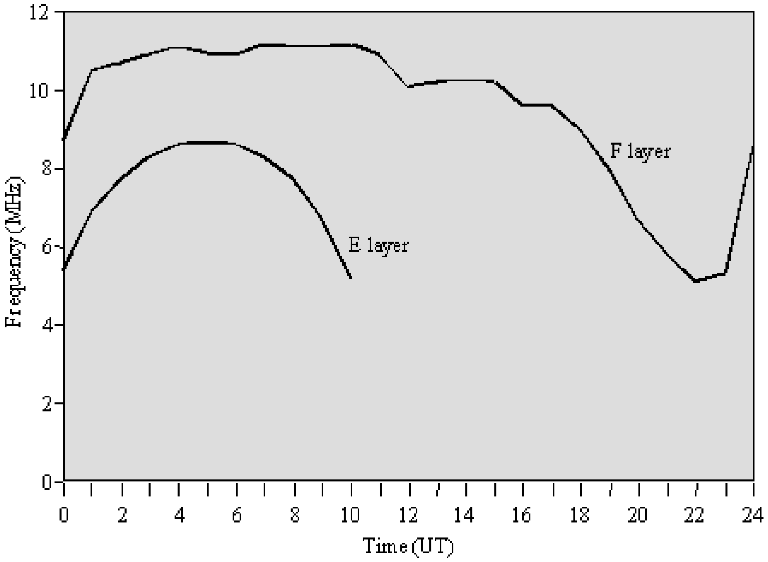


Figure 5. E and F layer frequencies for a Singapore to Ho Chi Minh circuit some time in a solar cycle.

## 5. *Variations in absorption*

The D region, which becomes insignificant at night, attenuates waves as they pass through it. Absorption was discussed in section 1 when describing how solar flares can cause disruptions or degradations to communication paths which pass through daylight. Absorption in the D region also varies with the solar cycle, being greatest around solar maximum. Signal absorption is greater in summer and during the middle of the day (see Figure 6). There is a variation in absorption with latitude, with more absorption occurring near the equator and decreasing towards the poles, although certain solar events will significantly increase absorption at the poles. Lower frequencies are absorbed to a greater extent.

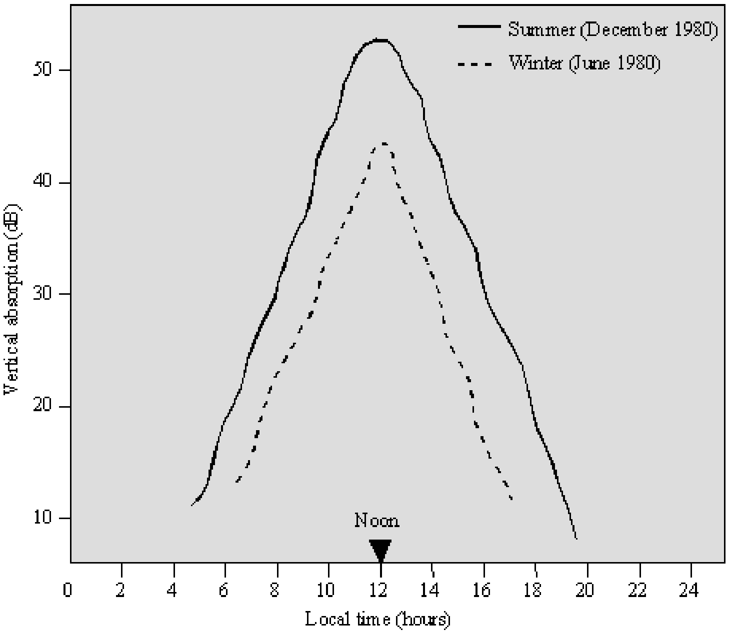


Figure 6. Example of diurnal and seasonal variations in absorption at Sydney, 2.2 MHz.

Around the polar regions absorption can affect communications quite dramatically at times. Sometimes high energy protons ejected from the Sun during large solar flares will move down the earth's magnetic field lines and into the polar regions. These protons can cause increased absorption of HF radio waves as they pass through the D region. This increased absorption may last for a number of days and is called a Polar Cap Absorption event (PCA, see definition).
(Reference: http://www.wulfden.org/NVQS/PropStuff/INTROHFP.HTM.)

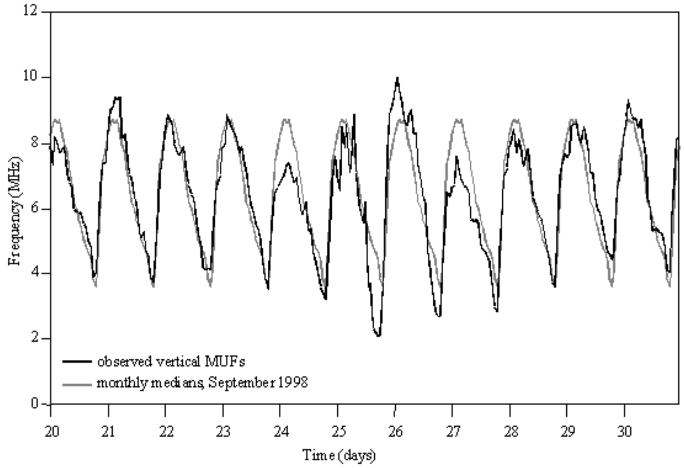
**Ionization:** Ionization is the process in which electrons, which are negatively charged, are removed from (or attached to) neutral atoms or molecules to form positively (or negatively) charged ions and free electrons (see ionosphere for more details).
(Reference: http://www.wulfden.org/NVQS/PropStuff/INTROHFP.HTM.)

**Ionospheric convection:** Ionospheric electric fields are the main result of the coupling between the magnetosphere and ionosphere. While at low-latitudes the ionospheric plasma is co-rotating with the earth, at higher latitudes it is convecting under the influence of the large scale magnetospheric electric field mapped to low altitudes. The Harang discontinuity is one of the ionospheric features related to the plasma convection pattern (see also convection and Harang Discontinuity).
(Reference: http://www.oulu.fi/~spaceweb/textbook/ionosphere.html.)

**Ionospheric dynamo:** The ionospheric dynamo is essentially that mechanism proposed by Stewart: winds in the thermosphere [90-500 km (56-311 miles)] move the conducting medium through the geomagnetic field, producing an electromotive force (emf) that drives currents and that sets up

polarization electric fields. Electric-potential differences of 5 kV to 10 kV between different parts of the globe are produced by this mechanism. The emf interacts only with the conductivity component transverse to the geomagnetic field, so that dynamo action is weighted toward the 90-150 km (56-93 miles) height range during the day. At night, however, the E-region transverse conductivity is greatly diminished, so that F-region dynamo action above 200 km (125 miles) becomes relatively more important. The ionospheric currents are strongest on the day side of the earth, where they typically form two large horizontal current vortices, clockwise in the southern hemisphere and counterclockwise in the northern hemisphere. The currents in the two hemispheres are connected by magnetic-field-aligned current when the dynamo effects in the two hemispheres are unbalanced.
(Reference: http://www.hao.ucar.edu/public/education/stp/EOS/EOS.html)

**Ionospheric storms:** Due to events on the Sun, sometimes the earth's magnetic field becomes disturbed. The geomagnetic field and the ionosphere are linked in complex ways and a disturbance in the geomagnetic field can often cause a disturbance in the F region of the ionosphere. These ionospheric storms sometimes begin with increased electron density allowing higher frequencies to be supported, followed by a decrease in the electron density leading to the successful use of only lower than normal frequencies of the F region. An enhancement will not usually concern the HF communicator, but the depression may cause frequencies normally used for communication to be too high with the result that the wave penetrates the ionosphere. Ionospheric storms may last for a number of days and mid and high latitudes are affected more so than the lower latitudes, generally. Unlike fade-outs (see short wave fade-outs), higher frequencies are most affected by ionospheric storms. Ionospheric storms can occur throughout the solar cycle and are related to coronal mass ejections (CMEs) and coronal holes on the Sun. The figure below shows how an ionospheric storm has caused frequencies in the main to be depressed at Canberra, Australia (a mid-latitude station) from 24 to 28th September 1998. Higher frequencies would probably have been unsuccessful over this time.

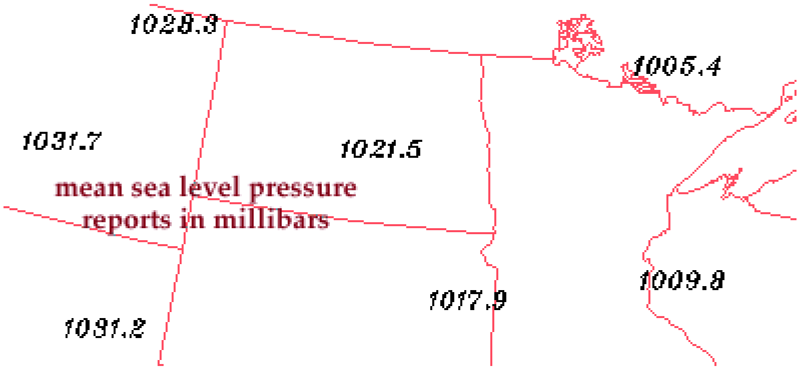


Canberra, Australia observed and median vertical MUFs for latter part September 1998. Significant depressions in F region frequencies occurred between 24 to 28 September due solar activity.
(Reference: http://www.wulfden.org/NVQS/PropStuff/INTROHFP.HTM.)

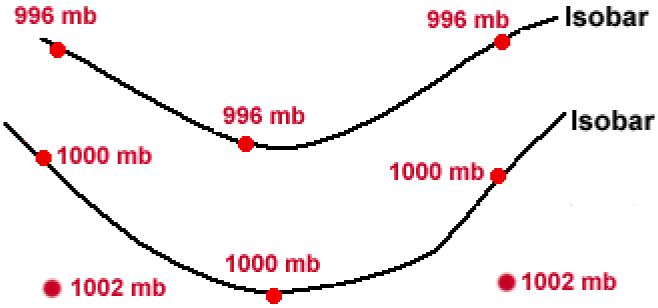
**Ionospheric troughs:** An ionospheric trough is a region of decreased F layer plasma density. At these altitudes the plasma depletion is due to decreased concentration of $O^+$.
(Reference: http://www.oulu.fi/~spaceweb/textbook/trough.html.)

**Ionospheric wind:** In the highly conductive ionosphere, the ions and free electrons move rapidly under the influence of electrical forces, this movement creates the ionospheric wind.
(Reference: http://www.auf.asn.au/meteorology/section1a.html#radiation_layers.)

**Isobars:** Lines of constant pressure. A line drawn on a weather map connecting points of equal pressure is called an "isobar". Isobars are generated from mean sea-level pressure reports and are given in millibars.

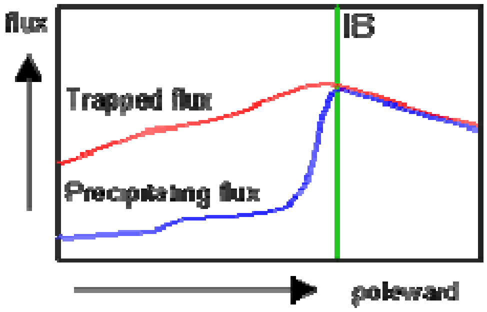


The diagram below depicts a pair of sample isobars. At every point along the top isobar, the pressure is 996 mb while at every point along the bottom isobar, the pressure is 1000 mb. Points above the 1000 mb isobar have a lower pressure and points below that isobar have a higher pressure.



(Reference: http://ww2010.atmos.uiuc.edu/(Gh)/wwhlpr/isobars.rxml?hret=/guides/mtr/fw/geos.rxml)

**Isotropic boundary, IB:** Observations of precipitating (Jp) and trapped (Jt) energetic (> 30 keV) particle fluxes at the ionospheric altitudes within the auroral oval region has revealed the existence of a sharp boundary separating the poleward zone of isotropic precipitation (Jp = Jt) from the equatorward zone of weak loss cone filling (Jp << Jt) at all local times. By definition, this boundary is called the isotropic boundary, IB. IBs have been studied mainly using the NOAA satellites in polar orbit at the altitude of about 800 km (500 miles).



(Reference: http://www.oulu.fi/~spaceweb/textbook/ib.html.)

**<u>Leader</u>:** (Or leader streamer or stepped leader.) The electric discharge that initiates each return stroke in a cloud- to-ground lightning discharge. It is a channel of high ionization that propagates through the air by virtue of the electric breakdown at its front produced by the charge it lowers. The stepped leader initiates the first stroke in a cloud-to-ground flash and establishes the channel for most subsequent strokes of a lightning discharge. The dart leader initiates most subsequent strokes. Dart-stepped leaders begin as dart leaders and end as stepped leaders. The initiating processes in cloud discharges are sometimes also called leaders but their properties are not well measured.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=leader1)

**<u>Lightning</u>:** Lightning is a transient, high-current electric discharge with pathlengths measured in kilometers (or miles). The most common source of lightning is the electric charge separated in ordinary thunderstorm clouds (cumulonimbus). Well over half of all lightning discharges occur within the thunderstorm cloud and are called intracloud discharges. The usual cloud-to-ground lightning (sometimes called streak lightning or forked lightning) has been studied more extensively than other lightning forms because of its practical interest (i.e., as a cause of injury and death, disturbances in power and communication systems, and ignition of forest fires) and because lightning channels below cloud level are more easily photographed and studied with optical instruments. Cloud-to-cloud and cloud-to-air discharges are less common than intracloud or cloud-to-ground lightning. All discharges other than cloud-to-ground are often lumped together and called cloud discharges. Lightning is a self-propagating and electrodeless atmospheric discharge that, through the induction process, transfers the electrical energy of an electrified cloud into electrical charges and current in its ionized and thus conducting channel. Positive and negative leaders are essential components of the lightning. Only when a leader reaches the ground does the ground potential wave (return stroke) affect the lightning process. Natural lightning starts as a bidirectional leader, although at different stages of the process unidirectional leader development can occur. Artificially triggered lightning starts on a tall structure or from a rocket with a trailing wire. Most of the lightning energy goes into heat, with smaller amounts transformed into sonic energy (thunder), radiation, and light. Lightning, in its various forms, is known by many common names, such as streak lightning, forked lightning, sheet lightning, and heat lightning, and by the less common air discharge; also, the rare and mysterious ball lightning and rocket lightning. An important effect of worldwide lightning activity is the net transfer of negative charge from the atmosphere to the earth. This fact is of great important in one problem of atmospheric electricity, the question of the source of the supply current. Existing evidence suggests that lightning discharges occurring sporadically at all times in various parts of the earth, perhaps 100 per second, may be the principal source of negative charge that maintains the earth–ionosphere potential difference of several hundred thousand volts in spite of the steady transfer of charge produced by the air–earth current. However, there also is evidence that point discharge currents may contribute to this more significantly than lightning.

Chalmers, J. A., 1957: Atmospheric Electricity, 235–255.
Schonland, B. F. J., 1950: The Flight of Thunderbolts, 152 pp.
Hagenguth, J. H., 1951: Compendium of Meteorology, 136–143.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=lightning1)

**Lightning channel:** The irregular path through the air along which a lightning discharge occurs. The lightning channel is established at the start of a discharge by the growth of a leader, which seeks out a path of least resistance between a charge source and the ground or between two charge centers of opposite sign in the thundercloud or between a cloud charge center and the surrounding air or between charge centers in adjacent clouds.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=lightning-channel1)

**Lightning discharge:** The series of electrical processes taking place within one second by which charge is transferred along a discharge channel between electric charge centers of opposite sign within a thundercloud (intracloud flash), between a cloud charge center and the earth's surface (cloud- to-ground flash or ground-to-cloud discharge), between two different clouds (intercloud or cloud-to-cloud discharge), or between a cloud charge and the air (air discharge). It is a very large-scale form of the common spark discharge. A single lightning discharge is called a lightning flash.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=lightning-discharge1)

**Lightning flash:** The total observed lightning discharge, generally having a duration of less than 1 second. A single flash is usually composed of many distinct luminous events that often occur in such rapid succession that the human eye cannot resolve them.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=lightning-flash1)

**Lightning stroke:** In a cloud-to-ground discharge, a leader plus its subsequent return stroke. In a typical case, a cloud-to-ground discharge is made up of three or four successive lightning strokes, most following the same lightning channel.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=lightning-stroke1)

**Lithosphere:** Brittle uppermost shell of the earth, broken into a number of tectonic plates. The lithosphere consists of the heavy oceanic and lighter continental crusts, and the uppermost portion of the mantle. The crust and mantle are separated by the Moho or Mohorovicic discontinuity. The thickness of the lithosphere varies from to around 1 mile (1.6 km) at the mid-ocean ridges to approximately 80 miles (130 km) beneath older oceanic crust. The thickness of the continental lithospheric plates is probably around 185 miles (300 km) but is uncertain due to the irregular presence of the Moho discontinuity. The lithosphere rests on a soft layer called the asthenosphere, over which the plates of the lithosphere glide. See plate tectonics.
(Reference: http://education.yahoo.com/reference/encyclopedia/entry?id=28292)

**Low-latitude aurorae:** Low-latitude aurorae are a storm time phenomena, in which particles originating from the ring current (and/or which are energized by the ring current) enter the lower thermosphere causing optical emission. It has been suggested that four "pure" types of such auroras exist, as shown in table below, where LEE = low energy electron aurora, and HP = heavy particle aurora. Many auroral events are a mixture of these "pure" types. For example, type d aurorae is considered to be a subset of type A aurorae.

| **Characteristics** | **"Pure" types** | | | | **Others** |
|---|---|---|---|---|---|
| | ***LEE (lowest)** | **LEE** | **HP Neutral** | **HP Ion** | |
| **Primaries** | <10 eV el. | ~10-1000 eV el. | ~1-100 keV HP | ~1-100 keV HP | mixed el. and HP |
| **Auroral names** | SAR arc | type d | neutral atom | ion<br>proton | low-latitude<br>type A<br>type I<br>great |
| **Dominant emission** | [OI] 630 nm | [OI] 630 nm | $N_2$+1N (vib. exc.) | $N_2$+1N (vib. exc.) | [OI] 630 nm or $N_2$+1N (vib. exc.) |
| **Red/green ratio r** | >10 | 1 < r < 10 | - | - | - |
| **Location** | near plasmapause | near plasmapause | equator to 40° ML | >40° ML | - |
| **Emission rate** | <10 kR | <1000 kR | <100 R | <10 kR | - |
| **Time scale** | ~10 hours | ~1 hour | ~1 hour | ~1 hour | - |
| * Here excitation by heat conducted from the magnetosphere is included | | | | | |

(Reference: http://www.oulu.fi/~spaceweb/textbook/low_lat_aurorae.html.)

**Magnetic dipole:** 1. In geomagnetism, either of the two points on the earth’s surface where a free-swinging magnetic needle points in a vertical direction. The line connecting these two points does not pass through the center of the earth. These two points constantly move at a slow rate. They are presently in northern Canada and in the Antarctic south of Australia. 2. See dipole.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=magnetic-dipole1)

**Magnetic field:** See magnetic induction.

**Magnetic induction:** A vector field, usually denoted by **B**, defined as follows.
The torque **N** experienced by a magnetic dipole with magnetic dipole moment **m** is

$$\mathbf{N} = \mathbf{m} \times \mathbf{B}.$$

Thus by measuring **N** for **m** oriented in two orthogonal (or perpendicular) directions, the magnetic induction components are obtained as torque components divided by the magnitude of **m**. The fundamental relation linking electric field **E** and magnetic induction **B** to the force on a charge *q* with velocity **v** is the Lorentz force equation

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}).$$

Magnetic induction is sometimes called magnetic field, a term usually applied to a different field **H**, related to **B** but different from it. In free space, **B** and **H** are proportional:

$$\mathbf{H} = \mathbf{B}/\mu_o,$$

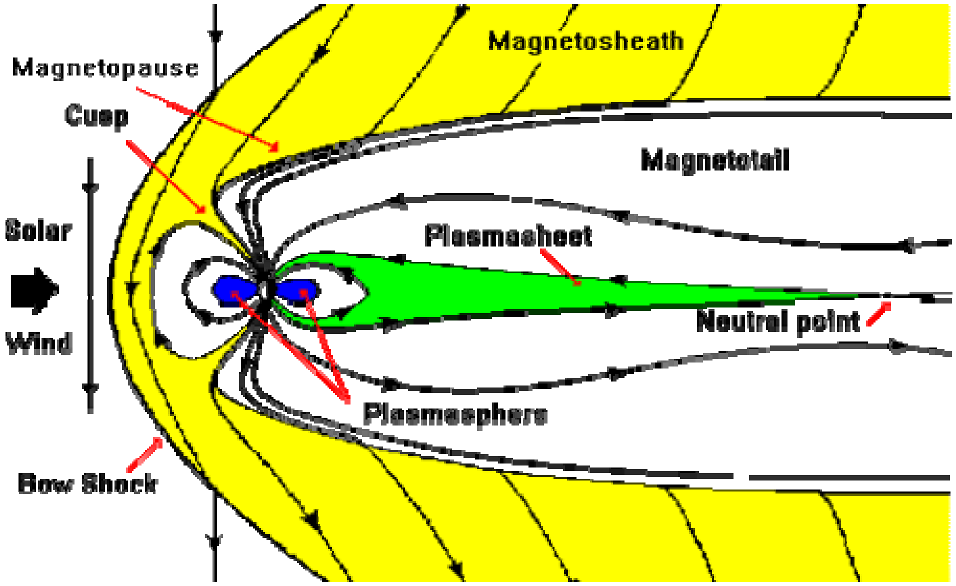
where $\mu_o$ , the permeability of free space, is a universal constant. **B** is the primitive field, whereas **H** is secondary, not strictly needed but convenient. Care must be exercised in deciding if, by magnetic field, **B** or **H** is meant. What is usually meant by the electric and magnetic fields (or the electromagnetic field) are **E** and **H**, although according to the Lorentz force equation **E** and **B** are the fundamental fields. Moreover, the Lorentz transformation preserves the (**E**, **B**) structure but not the (**E**, **H**) structure.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=magnetic-induction1)

**Magnetic latitude:** The geographic latitude of a location, in a system of latitudes and longitudes whose axis is not the rotation axis of the earth but the magnetic axis, i.e. the axis of the dipole at the earth´s center which best fits the internal magnetic field. The auroral zone, for instance, is near magnetic latitude 65 degrees.
(Reference: http://www-istp.gsfc.nasa.gov/Education/gloss.html.)

**Magnetic local time (MLT):** In the system of latitude and longitude whose axis is the dipole axis, magnetic local time is the longitude, measured not in degrees but in hours (1 hour = 15 degrees). The zero of this longitude is not fixed relative to earth (the way the Greenwhich meridian is for geographic longitude), but rather relative to the Sun: the line of magnetic longitude facing the Sun always has MLT = 12 hours ("magnetic noon"), and the opposite one has MLT = 0 or 24 hours ("magnetic midnight"). See magnetic latitude
(Reference: http://www-istp.gsfc.nasa.gov/Education/gloss.html.)

**Magnetosonic waves:** There are two magnetosonic waves. The first is generally termed the fast magnetosonic wave, or fast wave, for short, whereas the second is usually called the slow magnetosonic wave, or slow wave. These waves are associated with non-zero perturbations in the plasma density and pressure, and also involve plasma motion parallel, as well as perpendicular, to the magnetic field.
(Reference: http://farside.ph.utexas.edu/teaching/plasma/lectures/node64.html)

**Magnetosphere:** earth is one of the planets that has a strong internal magnetic field. In the absence of any external drivers, the geomagnetic field can be approximated by a dipole field with an axis tilted about 11 degrees from the spin axis. The forcing by the solar wind is able to modify this field, creating a cavity called the magnetosphere. This cavity shelters the surface of the planet from the high energy particles of the solar wind. The outer boundary of the magnetosphere is called the magnetopause. In front of the dayside magnetopause another boundary called the bow shock is formed because the solar wind is supersonic. The region between the bow shock and the magnetopause is called the magnetosheath. At low-altitude limit, the magnetosphere ends at the ionosphere. The magnetosphere is filled with plasma that originates both from the ionosphere and the solar wind.



(Reference: http://www.oulu.fi/~spaceweb/textbook/magnetosphere.html.)

The magnetosphere is the region of space where the geomagnetic field has a dominant influence on plasma properties. As the charged particles of the solar wind are deflected by the geomagnetic field, an electric current layer is formed at the boundary between the solar wind and the magnetosphere, called the magnetopause. This current layer distorts the geomagnetic field from the dipole-like configuration that it would otherwise have and helps to create a long magnetized tail trailing the earth. Although the full extend of this tail has not yet been determined, it is known to be more than 500 earth radii. The magnetosphere contains the radiation belt, composed of energetic charged particles trapped in the magnetic field. The number density of electron-ion pairs in the magnetosphere is highly variable, ranging in order of magnitude from a low of $10^6$ $m^{-3}$ in parts of the tail up to $10^{12}$ $m^{-3}$ in the densest portions of the dayside ionosphere.
(Reference: see # 10 in the reference section)

**Magnetospheric dynamo:** The solar wind/magnetospheric dynamo draws its energy from the kinetic and thermal energy of the solar wind and magnetospheric plasmas, generating electric fields and currents that connect to the high-latitude auroral and polar ionosphere along geomagnetic field lines. The nature of the solar wind/magnetosphere interaction depends strongly on the direction of the interplanetary magnetic field (IMF) that is embedded in the solar wind, since the direction of that field determines the topology of its connection with the earth's magnetic field. The ionospheric electric fields and currents produced by the solar wind/magnetospheric dynamo are usually much stronger than those of the ionospheric wind dynamo, and are highly variable in time. On the average, a high electric potential is established around 70-75° magnetic latitude on the morning side of the earth, and a low potential at around the same latitude on the evening side. The potential drop varies from 20 kV to 200 kV.
(Reference: http://www.hao.ucar.edu/public/education/stp/EOS/EOS.html)

**Magnetotellurics:** Magnetotellurics / Audio Frequency Magnetotellurics (MT/AMT). MT is a passive geophysical method, utilizing naturally occurring electromagnetic energy. The physical property of the subsurface measured is the electrical resistivity, familiar from the common electric logs. The fundamentals of MT are straightforward: Ohm's law is familiar; the statement that for an electric circuit the resistance (or impedance) can be computed exactly from a knowledge of the voltage and current. For electromagnetic waves, there is a similar formulation, Maxwell's equations, which relate the wave impedance to the ratio of the time-varying electric field to magnetic field, as a function of frequency. The wave impedance has units of resistivity (ohm-meters) and is termed the apparent resistivity. For an electromagnetic wave propagating into the earth and evaluated at the surface, the wave impedance, and thus the apparent resistivity, is a characteristic of a volume of the earth beneath the measurement site. For the MT electromagnetic waves, as with seismic waves, depth of penetration is a function of frequency. Seismic processors and interpreters know this, and time-varying filters where the frequency decreases with increasing depth are common in seismic data processing. In a similar fashion, a measurement of the MT apparent resistivity as a function of frequency may be related to actual resistivity as a function of depth and lateral distance from the measurement location. In addition, subsurface structure acts to distort the propagating (and re-radiated, or reflected) electromagnetic waves, leading to the reliable interpretation of structure from MT data. The measurement of time-varying electric and magnetic fields and the computation of apparent resistivity from these fields are precise, analytical steps and should be repeatable by any practitioner. The transition to depth from frequency is an interpretive step involving assumptions, the validity of which are case-dependent. The interpretation of geology based on vertical and lateral resistivity variations is, of course, an interpretive step. As an exploration tool, the application of MT requires that the target structure or stratigraphy involves resistivity contrasts or a known or estimated range of resistivities. Thus, in the overthrust application the detection of low resistivity clastics or porous carbonates beneath overthrust higher resistivity carbonates, volcanics, metamorphics, or crystalline rocks presents a valid target. Subthrust basement-related structure may often be identified, although detailed structural mapping is not generally considered an MT application. In difficult seismic country, MT is often used to identify poorly defined reflectors and to place bounds on the possible geologic interpretations. By identifying subthrust low-velocity clastics and then identifying high resistivity-low resistivity contacts that are related to high velocity-low velocity seismic contacts, MT results have proven to be of great value in resolving seismic processing as well interpretation ambiguities in these difficult seismic areas. Note that multiple carbonate thrust sheets with no intervening low resistivity "markers," or multiple low resistivity clastics with little resistivity variation, would, however, be difficult or impossible applications due to the minimal resistivity contrasts present for these examples. (Reference: http://www.aoageophysics.com/Electrical/MT-AMT/)

**Mantle:** Portion of the earth's interior lying beneath the crust and above the core. No direct observation of the mantle, or its upper boundary, has been made; its boundaries have been determined solely by abrupt changes in the velocities and character of seismic waves passing through the earth's interior (see seismology). Samples of the upper mantle may be provided by some volcanic eruptions in ocean areas, e.g., the Hawaiian Islands. The continental and ocean crusts, along with part of the solid upper mantle, make up the lithosphere to a depth of about 62 miles (100 km). Within the lithosphere is the Mohorovičić discontinuity, or Moho, considered to be the mantle's upper surface, at depths ranging from 4 to 43 miles (7 to 70 km). Analysis of seismic waves indicates that rocks below the Moho are less rigid and slightly more dense than rocks making up the crust. A zone of low seismic velocity and rigidity just below the lithosphere, called the asthenosphere, is present in the upper part of the mantle, from 62 mi (100 km) to 156 mi (250 km). Its presence is of critical importance to plate tectonics. The mantle continues to the Gutenberg discontinuity at the liquid outer core, with the base of the mantle located about 1,800 mi (2,900 km) below the earth's surface. The entire mantle constitutes about 84% of the earth by volume. Its composition is thought to be similar to peridotite, an igneous rock of mostly magnesium-rich silicate. (Reference: http://education.yahoo.com/reference/encyclopedia/entry?id=29953)

**Mesosphere:** The mesosphere is that layer, of the earth's atmosphere, which is directly above the stratosphere and directly below the thermosphere. The mesosphere is located 50 - 80/85 km (31 -50/53

miles) above earth's surface (see atmosphere). Within this layer, temperature decreases with increasing altitude. Temperatures in the upper mesosphere fall as low as 200°K, varying according to latitude and season. Millions of meteors burn up daily in the mesosphere as a result of collisions with some of the billions of gas particles contained in that layer. The collisions create enough heat to burn the falling objects long before they reach the ground. The stratosphere and mesosphere are referred to as the middle atmosphere. The mesopause, at an altitude of about 80 km (50 miles), separates the mesosphere from the thermosphere - the outermost layer of the earth's atmosphere.
(Reference: http://www.free-definition.com/Mesosphere.html.)

**Orogeny:** A major episode of plate tectonic activity in which lithospheric plates collide and produce mountain belts, in some cases including the formation of subduction zones and igneous activity. Thrust faults and folds are typical geological structures seen in areas of orogeny. Alternate form: orogenic.
(Reference: http://www.glossary.oilfield.slb.com/Display.cfm?Term=orogeny)

**Pantograph**: A collapsible and adjustable piece of equipment on top of an electric locomotive which allows contact with overhead wires. (Several definitions exist. The definition given here is in relation with the context in which the word is used in this website.)
(Reference: http://www.google.com/search?hl=en&lr=&oi=defmore&q=define:Pantograph)

**Paleomagnetism:** Study of the intensity and orientation of the earth's magnetic field as preserved in the magnetic orientation of certain minerals found in rocks formed throughout geologic time. Paleomagnetic studies of rocks and ocean sediments have demonstrated that the orientation of the earth's magnetic field has frequently alternated over geologic time. Periods of "normal" polarity (i.e., when the north-seeking end of the compass needle points toward the present north magnetic pole, as it does today) have alternated with periods of "reversed" polarity (when the north-seeking end of the compass needle points southward). The cause of these magnetic "flip-flops" is not clearly understood. Ideas of paleomagnetism began in the late 1920s, when French physicist Mercanton, suggested that because today's magnetic field is close to the earth's rotational axis, continental drift could be tested by ascertaining the magnetic characteristics of ancient rocks; however, it was not until after World War II that rock paleomagnetism data was gathered. Paleomagnetism is possible because some of the minerals that make up rocks–notably magnetite–become permanently magnetized parallel to the earth's magnetic field at the time of their formation. Rocks from hot liquid magma, or even minerals made up of crystals that grow at low temperatures, can acquire magnetization. Also, when magnetized minerals become disaggregated from their parent rocks by erosion and are carried into a basin, they will tend to align themselves parallel to the earth's magnetic field as they settle in still water. When the deposit into which they settle hardens into rock, the magnetization will be fixed. Geophysicists have been able to trace changes in the orientation of the earth's magnetic field through geologic time by carefully collecting rock specimens of different ages and determining the alignment of their magnetic fields. That technique has provided a timetable for periods of normal and reversed polarity, showing 171 reversals in the earth's magnetic field in the past 76 million years. Paleomagnetic studies of the ocean floor have been of decisive importance in establishing the modern theories of continental drift and seafloor spreading.
(Reference: http://education.yahoo.com/reference/encyclopedia/entry?id=35720)

**Planetary boundary layer:** The planetary boundary layer (PBL) is that region of the lower atmosphere in which the influences of the earth's surface are directly felt. The primary influences of the surface are drag, heating (or cooling), and evaporation (or condensation). These processes cause vertical fluxes of momentum, sensible heat, and moisture, which penetrate into the lower atmosphere to a finite height. These fluxes, in turn, generate turbulence, ultimately controlling the mean profiles of wind speed, temperature, and water vapor in the PBL. Since the height of penetration depends on the direction, magnitude, and persistence of the surface fluxes and on the large-scale meteorological conditions, the PBL can range in thickness from tens of meters to a few kilometers.

Most atmospheric processes are interrelated and cannot be studied in isolation, but it is usually possible to identify one or two dominant influences. In the case of atmospheric electricity in the PBL, however, separating the various causes and their effects can be extremely difficult. In fact, this field may be unique with respect to its sensitivity to many disparate phenomena spanning a tremendous range of scales in both space and time. For example, locally produced turbulent fluctuations in space-charge density have an effect roughly comparable in magnitude to that of changes in global thunderstorm activity on electric-field variations in the PBL. Over the years this responsiveness of atmospheric electricity had led to its exploitation for many different purposes. Electrical measurements have been made in the PBL to observe large-scale processes such as the global circuit, to study local phenomena like boundary-layer turbulence, or simply to examine unusual electrical signatures in their own right. In each type of investigation it has been found necessary to minimize the effects of unwanted processes on the data. This filtering is never entirely successful, however, and investigators must always be aware of the whole range of influences and alert for contamination. While atmospheric-electrical variables respond to many processes, they usually have little influence on the phenomena to which they respond. Thus the electrical state of the PBL is irrelevant to the fields of environmental radioactivity, air pollution, boundary-layer turbulence, and global meteorology, for example. The inverse is not true, however. Atmospheric electricity in the PBL is a truly interdisciplinary study requiring a knowledge of all these areas in addition to ionic conduction in gases, aerosol physics, and electrostatics.

## Physical Mechanisms That Affect Atmospheric Electricity in the Planetary Boundary Layer:

### *Ionization:*

The electrical conductivity of the air is due to ions produced primarily by ionizing radiation. The early investigations of the sources of atmospheric ions led to the discovery of cosmic rays. Cosmic radiation is the primary source of ions over the oceans and above a couple of kilometers over land. In the PBL the cosmic-ray contribution to the ionization rate is about 1 to 2 ion pairs per cubic centimeter per second. It is quite constant in time, and the latitudinal dependence caused by the earth's magnetic field is well understood.

The primary source of ions in the PBL over land is natural radioactivity originating fron the ground. This ionization source can be divided into two parts: (i) αs, βs, and γs radiating directly from the earth's surface and (ii) radiation from radioactive gases and their radioactive daughter products exhaled from the ground. The gases originate in both the uranium and the thorium decay series where one of the daughters is the noble gas, radon. It is obvious that radiation directly from the ground will vary greatly depending on the geographical variations in ground radioactivity. Ground radiation intensity also decreases with height; α ionization is confined to the first few centimeters, β to the first few meters, and γ to the first few hundred meters. The amount of ionization in the first few centimeters resulting from αs is largely unknown. Values of ionization due to βs in the first few meters are typically in the range of 0.1 to 10 and those due to γs in the lowest hundred meters are in the range of 1 to 6 ion pairs $cm^{-3}$ $sec^{-1}$. On cool nights with nocturnal temperature inversions the radioactive gases can be trapped in a concentrated layer close to ground, whereas during unstable convective periods, the gases can be dispersed over an altitude of several kilometers. Ionization at 1 to 2 m due to radioactive gases and their short-lived daughter products is typically in the range of 1 to 20 ion pairs $cm^{-3}$ $sec^{-1}$ and is predominantly caused by α particles. Ionization due to cosmic rays is nearly constant in the first kilometers. The ionization from ground β and γ radiation will vary geographically depending on the abundance of radioactivity in the local soil. Compared with the ionization due to natural sources, ionization from nuclear power plants and weapons is negligible on a global scale. This was true even during the active period of nuclear weapons testing in the 1950s and 1960s. There can, of course, be locally significant effects.

In addition to ionizing radiation, electrical discharges can also form ions in the atmosphere. This requires high electric fields that generally occur only in disturbed weather near thunderstorms and in regions of blowing dust or snow. The field is greatly augmented at points on electrically grounded, elevated objects such as vegetation and antennas. As the electric field increases, the field in very small regions near such points reaches breakdown values and a small ionic current is discharged into the atmosphere. A large number of unipolar ions are injected locally into the atmosphere, and the ionic space charge thus formed tends to reduce the high electric field. Ions can also be produced by the bursting of water films. In nature this occurs in waterfalls, falling rain, and breaking waves. Ions generated by this mechanism are not formed in pairs, and a net charge is introduced into the atmosphere. In most cases the residue remaining after evaporation of the water is much larger than a small ion and is more appropriately identified as a charged aerosol particle.

*Properties of Ions:*

The radioactive ionization process separates an electron from a molecule of nitrogen or oxygen. The electron attaches rapidly to a neutral molecule to form a negative ion. During the next few milliseconds both positive and negative ions undergo a series of chemical, charge-exchange, and clustering reactions with the molecular species present in the air. Much progress has recently been achieved in understanding this chain of ionic reactions in well-defined laboratory gases and in the upper atmosphere. In the troposphere, where trace gases are numerous and variable, the ion chemistry is complicated, and the composition of the terminal ion must be regarded as uncertain at best. Fortunately, the ion nature enters the equations that govern atmospheric electricity in the PBL only as it affects the ionic mobility and recombination coefficient. The mobility is defined as the mean drift velocity of the ion per unit electric field. The mobilities of ambient ions are more easily determined than their mass or chemical composition. Values for aged positive and negative ion mobilities at STP (standard temperature and pressure) are about 1.15 and 1.25 $cm^2V^{-1}sec^{-1}$, respectively, are inversely proportional to air density, and are independent of electric-field strength.

*Attachment of Ions to Aerosol Particles:*

In most continental areas the loss of ions by attachment to aerosol particles is greater than the loss by ion-ion recombination. The attachment process also establishes a size-dependent statistical charge distribution on the aerosol particles. (Some are negatively, some positively, and some neutrally charged.)

Effect of the Global Circuit: Electric fields and currents in the PBL arise primarily from the voltage impressed across it by the global circuit. The weak conductivity of the PBL causes it to act as a resistive element in the global circuit, conducting a fair-weather current density of about 1 to 3 $pA/m^2$ to ground where the fair-weather electric field is about 100-200 V/m. Because the PBL is the region of greatest electrical resistance, it largely controls the discharge rate of the global circuit.

If the conductivity of the atmosphere were uniform, it would be a passive ohmic medium with no accumulation of space charge to alter the electric field. Space charge is generated internally in the unperturbed atmosphere in two ways: (1) by conduction down a conductivity gradient and (2) by the imbalance of ion flow near a boundary. The first mechanism can be understood in terms of Ohm's law. For steady-state conditions and in the absence of any convective charge transport, the conduction-current density is uniform, and, therefore, the electric field is inversely proportional to the conductivity. Since conductivity changes with altitude, there must be an inverse altitude dependence of the electric field. Poisson's equation requires this change in field to be accompanied by a space charge. The space charge is proportional to the electric field and conductivity gradient and inversely proportional to the conductivity. This process can be thought of as a pileup of space charge due to conduction down a conductivity gradient. The second mechanism for producing space charge operates only near a boundary. Across any horizontal area in the atmosphere stressed by a vertical electric field, positive and negative ions will flow in opposite directions. However, at a boundary, ions of one sign can flow to that boundary, bur there will be no compensating flow of the opposite sign away from it. This imbalance in ion flow gives rise to a space charge in the vicinity of the boundary. This second mechanism for generating space charge is aptly referred to as the electrode effect. For the case of uniform volume ionization in laminar airflow with no aerosols and bounded on the bottom by a conductive surface, the solution of the ion-balance equation together with Poisson's equation predict that the effect of the electrode, in this idealized case, would extend to about 3 meters. In the turbulent atmosphere, the electrode effect extends to much higher altitudes and the space charge formed by these two mechanisms is dispersed by turbulent mixing, causing a convective flux of charge in addition to the conduction current.

### *Turbulent Transport of Electrical Properties:*

Most aspects of the structure of the PBL are dominated by the effects of turbulence, and electrical processes are no exception. Turbulent mixing prevents the buildup of radioactive emanations in shallow layers near the ground except under very stable conditions, disperses aerosols over a greater depth increasing the columnar resistance, and redistributes space charge, producing convection currents. The almost continual state of turbulent motion in the atmosphere is caused by the combined influences of drag, heating, and evaporation from the underlying surface. It is only in cases of extremely low wind speed and strong surface cooling that laminar flow may be found, and even then only for short periods and over limited areas.

Electric field fluctuations are also caused by turbulent movement of the space charge present in the PBL. To specify the average electric field, the instantaneous field must therefore be averaged over an interval of time longer than the period of the largest eddy.

It is obvious from this discussion that any treatment of atmospheric electricity in the PBL must include the effects of turbulence.

## Phenomenology of Atmospheric Electricity in the Planetary Boundary Layer

Although typical average values are often cited for atmospheric-electrical observables, the greatest interest and significance by far has been attached to variations with time over a broad range of time scales. There have been studies of atmospheric-electrical variations with annual and even 11-year periodicities; short-period fluctuations have also received some attention in the past, and they are currently a subject of renewed interest. By far the greatest effort has been focused on diurnal variations with respect to either universal or local time and, to a lesser extent, on seasonal changes in diurnal patterns. One of the first, and certainly the most famous, demonstrations of a reproducible variation pattern with universal time is the hourly average potential gradient curves obtained over the world ocean on the Carnegie cruises in 1928-1929. These curves have long served as de facto standards with which to evaluate the viability of attempts to measure universal variations (see the historical note at the end of the Global Electrical Circuit section). Quasi-continuous measurements of current density made above the PBL during the Arctic winter, when allowance is made for the small (6 percent) measured change in columnar resistance during the measurement period, should accurately mirror variations in ionospheric potential. Consideration of these curves strongly indicates that there is indeed a well-defined average global diurnal variation but that there are equally important and real local deviations with time. In effect it has been demonstrated that the effect of turbulent processes on warmer (March to October) afternoons can dominate the average diurnal curve. For this reason a better knowledge of ionospheric potential variations would play a key role in the identification of effects attributable to PBL processes.

Electric field and vertical current density are driven by the global circuit and can exhibit the characteristic variation pattern (high in the afternoon and low at night) even within the PBL in certain cases if suitably averaged. There are other observables such as the ionic conductivity, which are only weakly influenced by global processes while depending strongly on local effects. Conductivity has been seen to be a result of ionization, ionic mobility, recombination, and attachment of ions to particulates, all of which can be influenced by local conditions and variable trace constituents. It is reasonable therefore to expect that large variations in conductivity will be primarily determined within the PBL and have a marked dependence on local time. The columnar resistance is a parameter usually defined as the resistance of a vertical column of unit cross-section from ground level to the base of the ionosphere. It is commonly derived from a measured vertical profile of atmospheric conductivity, and it is observed that most of this resistance lies within the PBL.

The strong effect of the midday upward dispersion of aerosols on columnar resistance results in the shape of the columnar resistance curve to show about 40% variation between its higher (early afternoon) and lower (early morning) points. This variation is in reasonable accord with the current knowledge of the daily variation of turbulent activity. The strong dependence of the columnar resistance on PBL conditions provides a mechanism for the modification of electrical observables with local time. Such mechanisms can embrace the entire PBL as does fully developed turbulent convection, or they can be confined to a shallow region near the surface. One example of a shallow effect is seen in the observed response to the typical urban morning rush hour. In the morning there is still little turbulence activity, since solar heating of the surface has just begun, and there is an abrupt injection of combustion products into the stratified atmosphere. Conductivity is reduced by particulates, but this reduction is confined to a shallow layer; so the total columnar resistance and thus the vertical current are largely unaffected. Consequently, the local surface electric field increases as required by Ohm's law (and so does the electric surface potential). Because of these diurnal variations, single-station potential gradient recordings, even when heavily averaged, rarely exhibit a classical Carnegie-type diurnal variation pattern. These diurnal variations with both universal and local time are not the only fluctuations observed in atmospheric-electricity recordings. Shorter-period variations are always observed and usually dismissed as noise. Observed fluctuations on atmospheric-electricity recordings made within the PBL are comparable in magnitude to the mean values of those recordings. Much of the fluctuation content in the range from roughly 0.1 second to tens of minutes is produced by local turbulence.

Although horizontal gradients of atmospheric-electrical variables within the PBL are much smaller than vertical ones (largely a consequence of the geometric scales involved), significant horizontal variability is observed. Significant instances include the effect of organized convection activity on a large scale, terrain effects produced by mountains and coastlines, and the sunrise effect caused by differences in turbulent mixing between the heated and dark regions. To a first approximation such effects are seen to be the result of imposition of a local perturbation on an otherwise uniform situation and are, hence, essentially comparable with local phenomena such as the rush-hour effect previously described.

The spatial variation on which attention has been focused is in the vertical dimension. The interest in global-scale phenomena has led to the use of a vertical profile as a convenient observational unit. Measurements are made of one or more atmospheric-electrical variables, typically field, conductivity, and/or current density, at a variety of altitudes in a relatively short time span (from a few to tens of minutes). The sensors are carried aloft with aircraft, balloons, or rockets, and data are presented both as profiles and as numerically integrated totals. Profiles have been made over land because of convenience and to study specific terrain effects and over water in attempts to eliminate land effects. Profile data have been responsible for the detection of convection currents in the PBL comparable in magnitude with the total current, the classical electrode effect over water under stable conditions, the response of columnar resistance to pollutant buildup, and the classical diurnal variation in ionospheric potential. The vertical profiles of atmospheric potential through the PBL taken over Greenland are characterized by extremely low levels of particulate contamination, and the vertical variation of conductivity closely approximates that predicted theoretically for an aerosol-free atmosphere. The addition of particulate burdens, whether in a shallow layer as in the California coast or in a thick layer as in Virginia, markedly affects the observations within the PBL. It is apparent that, in the presence of atmospheric contaminants, the voltage drop across the PBL is significantly greater than in the Greenland observations.

The conduction-current density, defined as the product of electric field and conductivity, can easily be computed from airborne measurements. Above the PBL the current density is essentially constant with altitude. This is a direct result of the small space-charge density above the PBL and the greatly reduced turbulent mixing found there. This vertical constancy led to the aforementioned use of current-density measurements above the PBL to follow universal variations. The increases seen at low altitudes were the first unambiguous evidence of the existence and significant magnitude of convective charge transport within the PBL.

In addition to variations that depend on time or height are variations that are associated with a specific phenomenon. The most well known such case is the atmospheric-electric fog effect. It has been observed that the conductivity decreases markedly in fog and that the start of the decrease may precede the actual fog onset. Analogously, the increase in conductivity at the termination of the fog event may also precede actual dissipation. This phenomenon has been reported by many observers, but it has not yet received as adequate physical analysis.

Similarly, there are effects associated with surf and waterfalls wherein some charge separation is produced by mechanical breakup of the water surfaces. For example, the positive space charge produced by breaking surf can lead to an appreciably larger electric field on shore than outside the surf zone during onshore winds. In contrast to the positive charge produced along ocean coasts, sufficient negative charge has been observed along the shore of a freshwater body (Lake Superior) during heavy surf to reverse the fair-weather electric field. Negative charge is also observed from waterfalls. In some cases there are also strong local effects associated with smoke plumes and with volcanic eruptions. Again there is a separation of charge, which then diffuses away from the source.

## Modeling and Theory

The complicated dependencies of the local electrical variables on the ionization profile, aerosol concentrations, turbulent structure of the PBL, and temporal variations in the global electrical circuit make it dangerous to trust intuitive notions when interpreting measurements in the PBL. Increased insight into the meaning of the observations is obtained by modeling various physical mechanisms mathematically.

The electric field tends to be nearly vertical in fair weather, and the meteorological structure of the PBL usually changes slowly in comparison to the electrical relaxation time. This has led naturally to the assumption of a quasi-steady, horizontal homogeneous mean state and to one-dimensional, time-independent models of the mean electrical structure. These assumptions imply that the conduction and convection current densities are vertically directed and that their sum, the total current density, is height independent, leading to great simplifications from a modeling point of view. About this mean state, of course, are fluctuations caused by turbulent eddies.

The primary goal of electrical modeling of the boundary layer to date has been to understand the mean profiles of the electrical variables resulting from currents driven by the global circuit. Thus, theoretical developments have focused on the sources of charge within the PBL and the phenomena produced by the vertical turbulent transport of that charge.

### *The Electrode Effect:*

The electrode effect has already been defined, and its simplest manifestation has been described for laminar flow and uniform ionization in aerosol-free air. In this case the electrode layer has a thickness of only a few meters, over which the electric-field magnitude decreases by about a factor of 2. The importance of the phenomenon lies in its ability to separate substantial amounts of charge near the earth's surface. In conditions of low turbulence this leads to high space-charge densities in shallow layers, which can produce high electrical noise levels as intermittent eddies move this charge around. In strongly unstable conditions, on the other hand, it provides a source of charge to be carried deep into the interior of the PBL by convection currents. The theory of the nonturbulent electrode effect is fully developed and has been verified over water and, at least qualitatively, over land.

The most obvious effect of turbulence on the electrode layer is to increase its thickness by mixing the space charge upward. The impact of nonuniform ionization is reduced as the turbulence intensity increases, both because trapping of radioactive emanations is eliminated and because the thicker layer appears to be less sensitive to surface radioactivity. The presence of aerosol particles thickens the layer further, in contrast to their effect in the nonturbulent case, by increasing the electrical relaxation time. These processes may increase the height scale of the electrode layer so much as to make it virtually undetectable with surface-based measurements. For this reason turbulence blurs the distinction between the electrode effect proper and convective currents in the interior of the PBL. Turbulence can also cause significant loss of ions and space charge by diffusion to the surface. The theory of the turbulent electrode effect is not so fully developed as that of the nonturbulent case, owing primarily to the difficulty of parameterizing the lower boundary conditions at an aerodynamically rough surface.

### *Convection Currents in the Planetary Boundary Layer:*

Recent modeling of convection currents has shown that they only become important in unstable mixed layers, where the turbulent transport time across the entire PBL can be comparable with the electrical relaxation time. The controlling meteorological variables are the surface fluxes of momentum and buoyancy and the mean conductivity and thickness of the mixed layer.

### *Effect of the Planetary Boundary Layer on the Fair-Weather Electrical Circuit:*

Two boundary-layer processes can have a substantial impact on the fields and currents appearing throughout the entire atmospheric column from the earth to the ionosphere. These are variations in the columnar resistance and convection currents.

If we assume a steady ionospheric potential, a steady-state model of the fair-weather electrical circuit shows that the magnitude of the total current density is inversely proportional to the total columnar resistance and decreases linearly as the boundary-layer electromotive force (EMF) increases. An aerosol-related increase in columnar resistance of 40% can therefore produce a similar decrease in the total current density. A simultaneous 100-kV increase in the PBL EMF can cause a further 30% decrease, for a total reduction in current density of 52%. This makes the total current density alone a relatively poor indicator of global processes.

## Needed Research and Potential Applications

### *Measurement of Global-Scale Phenomena:*

Unfortunately, the measurement of global-circuit parameters is complicated by the action of boundary-layer processes. Although local PBL structure cannot appreciably affect the total current in the global circuit, or even the local ionospheric potential, it can cause a redistribution of that current and alter the vertical profile of electric field. Therefore, the proper interpretation requires a thorough understanding of noise sources in the PBL.

The electrostatic potential of the upper atmosphere with respect to earth is the single parameter most indicative of the electrical state of the global circuit. Yet the temporal variability of this ionospheric potential is largely unknown outside of its average diurnal variation. Methods of measuring the ionospheric potential (such as aircraft and balloon soundings) have for the most part systematically excluded the detection of any shorter-term variations. Fluctuations in electric-field and current-density measurements in the PBL with periods shorter than a few hours are usually attributed entirely to local sources, primarily turbulence and pollution.

If it can be demonstrated that short-period and day-to-day global variations do indeed exist, then not only is the source of these variations of importance but also the usual interpretation of local variations in terms of turbulence must be re-evaluated. In light of the importance of the ionospheric potential as an indicator of the electrical state of the global circuit and the need to separate its variations from local fluctuations in the PBL, the ionospheric potential should be measured continuously and simultaneously at two or more locations for a period of days and with a time resolution of seconds, preferably in conjunction with observations of global thunderstorm activity and of upper-atmospheric disturbances.

*Potential Tool for Study of Planetary-Boundary-Layer Turbulence:*
Areas of particular ignorance at present are the ionization rate within the plant canopy and the disposition of space charge accumulating at an inversion because of the discontinuity of the conductivity usually found there. Further research into these areas may eventually lead to the use of atmospheric-electrical measurements to observe, perhaps remotely, the meteorological structure of the PBL.

*Ion Physics and Balance in the Planetary Boundary Layer:*
Small atmospheric ions, existing by virtue of a balance between ionization of the neutral gas and recombination and attachment to aerosol particles, cause the conductivity of the air. Yet many facets of the nature and behavior of these particles are still poorly understood.

The use of conductivity or columnar resistance as a pollution monitor depends on the inverse relationship between conductivity and aerosol burden. The conductivity is sensitive to aerosol concentration, and measurements spanning several decades have been used to evaluate changes in global particulate pollution.

The electrical state of the atmosphere depends critically on the ionization profile. Over the ocean ionization is due only to cosmic rays, and oceanic measurement of the electrode effect are in satisfactory agreement with numerical solutions of the governing equations. Over land, the ionization profile is complicated owing to ionization from ground radioactivity and radioactive gases as discussed earlier. Simultaneous measurement of all contributions to the ionization profile has never been accomplished.
(Reference: see # 10 in the reference section)

**Plasma:** Matter in the known universe can be classified in terms of four states: solid, liquid, gaseous, and plasma. The basic distinction between solids, liquids and gases lies in the difference between the strength of the bonds that hold their constituent particles together. The equilibrium between particle thermal (= random kinetic) energy and the inter-particle binding forces determines the state. Heating of a solid or liquid substance leads to phase transition to a liquid or gaseous state, respectively. This takes place at a constant temperature for a given pressure, and requires an amount of energy known as latent heat. On the other hand, the transition from a gas to an ionized gas, i.e., plasma, is not a phase transition, since it occurs gradually with increasing temperature. During the process, a molecular gas dissociates first into an atomic gas which, with increasing temperature, is ionized as the collisions between atoms are able to free the outermost orbital electrons. Resulting plasma consists of a mixture of neutral particles, positive ions (atoms or molecules that have lost one or more electrons), and negative electrons. In a weakly ionized plasma, such as the ionosphere, the charge-neutral interactions are still important, while in strongly ionized plasma the multiple Coulomb interactions are dominant.
(Reference: http://www.oulu.fi/~spaceweb/textbook/plasma.html.)

**Plasma sheet and PSBL:** The plasma sheet is the region of closed field lines in the equatorial magnetotail (see magnetosphere and picture therein; see also plasmoids). The plasma sheet is typically divided into plasma sheet proper, or central plasma sheet, and plasma sheet boundary layer (PSBL), the latter being at higher latitudes adjacent to the tail lobes. It is also divided into two parts by the cross-tail current sheet in the equatorial plane. However, as the plasma sheet extends from the magnetotail to the geosynchronous orbit, the effects of the current are not as important in the inner plasma sheet as further tailward, and the magnetic field geometry has a transition region between the inner dipolar form and outer taillike field. The plasma sheet is a very important region for auroral physics, since the nighttime auroral oval maps to it (to what radial distances is an unanswered question). The diffuse aurora originates from a region closer to earth than the discrete aurora.
(Reference: http://www.oulu.fi/~spaceweb/textbook/plasma_sheet.html.)

**Plasmasphere and plasmapause:** The plasma in the inner magnetosphere co-rotates with the earth. As a consequence, the ionospheric plasma at mid-latitudes can expand upward along the magnetic field lines and fill them until the plasma gas pressure is equalized along the entire field line. The plasma region above the ionosphere on such closed magnetic field lines is called the plasmasphere. In fact, the plasmasphere can be considered as an extension of the ionosphere, for there is no clear distinction between them. The outer boundary of the earth-encircling plasma is called the plasmapause. In the first approximation, the plasmasphere lies just inside the ring current and the plasma sheet field lines. (Reference: http://www.oulu.fi/~spaceweb/textbook/plasmasp.html.)

**Plasmoids/flux ropes:** Tailward fast plasma flows with dipolar Bz signatures (north-then-south turning of the magnetic field B) observed within the plasma sheet are called plasmoids. Most plasmoids have also helical magnetic field structures (large By fields), called "flux ropes". Total pressure enhancement is a necessary condition for plasmoids: enhancement if the plasma (magnetic) pressure correspond to a magnetic island (flux rope) type plasmoid. In the tail lobe, a travelling compression region is often observed, and is interpreted as a remote manifestation of a plasmoid passage.
(Reference: http://www.oulu.fi/~spaceweb/textbook/substorms/plasmoids.html.)

**Plate tectonics:** Theory that unifies many of the features and characteristics of continental drift and seafloor spreading into a coherent model and has revolutionized geologists' understanding of continents, ocean basins, mountains, and earth history.

Development of Plate Tectonics Theory

The beginnings of the theory of plate tectonics date to around 1920, when Alfred Wegener, the German meteorologist and geophysicist, presented the first detailed accounts of how today's continents were once a large supercontinent that slowly drifted to their present positions. Others brought forth evidence, but plate tectonics processes and continental drift did not attract wide interest until the late 1950s, when scientists found the alignment of magnetic particles in rock corresponded to the earth’s magnetic field of that time. Plotting paleomagnetic polar changes (see paleomagnetism) showed that all continents had moved across the earth over time. Synthesized from these findings and others in geology, oceanography, and geophysics, plate tectonics theory holds that the lithosphere, the hard outer layer of the earth, is divided into about 7 major plates and perhaps as many as 12 smaller plates, about 60 miles (100 km) thick, resting upon a lower soft layer called the asthenosphere. Because the sides of a plate are either being created or destroyed, its size and shape are continually changing. Such active plate tectonics make studying global tectonic history, especially for the ocean plates, difficult for times greater than 200 million years ago. The continents, which are about 25 miles (40 km) thick, are embedded in some of the plates, and hence move as the plates move about on the earth’s surface. The mechanism moving the plates is at present unknown, but is probably related to the transfer of heat energy or convection within the earth’s mantle. If true, and the convection continues, the earth will continue to cool. This will eventually halt the mantle's motion allowing the crust to stabilize, much like what has happened on other planets and satellites in the solar system, such as Mars and the moon.

Plate Boundary Conditions

There are numerous major plate boundary conditions. When a large continental mass breaks into smaller pieces under tensional stresses, it does so along a series of cracks or faults, which may develop into a major system of normal faults. The crust often subsides, forming a rift valley similar to what is happening today in the Great Rift Valley through the Red Sea. If rifting continues, a new plate boundary will form by the process of seafloor spreading. Mid-ocean ridges, undersea mountain chains, are the locus of seafloor spreading and are the sites where new oceanic lithosphere is created by the upwelling of mantle asthenosphere. Individual volcanoes are found along spreading centers of the mid-ocean ridge and at isolated "hot spots," or rising magma regions, not always associated with plate boundaries. The source of hot-spot magmas is believed to be well below the lithosphere, probably at the core-mantle boundary. Hot-spot volcanoes often form long chains that result from the relative motion of the lithosphere plate over the hot-spot source. Subduction zones along the leading edges of the shifting plates form a second type of boundary where the edges of lithospheric plates dive steeply into the earth and are reabsorbed at depths of over 400 miles (640 km). earthquake foci form steeply inclined planes along the subduction zones, extending to depths of about 440 miles (710 km); the world's most destructive earthquakes occur along subduction zones. A third type of boundary occurs where two plates slide past one another in a grinding, shearing manner along great faults called strike-slip faults or fracture zones along which the oceanic ridges are offset. Continental mountain ranges are formed when two plates containing continental crust collide. For example, the Himalayas are still rising as the plates carrying India and Eurasia come together. Mountains are also formed when ocean crust is subducted along a continental margin, resulting in melting of rock, volcanic activity, and compressional deformation of the continent margin. This is currently happening with the Andes mountains and is believed to have occurred with the uplift of the Rockies and the Appalachians in the past.

Movement of the Continents

According to plate tectonics, the ocean basins are viewed as transient features that have periodically opened and closed, first rending and then suturing the continental masses, which are permanent features on the earth’s surface. Geologists now believe that the continents were sutured together 200 million years ago at the beginning of the Mesozoic era to form a supercontinent named Pangaea. Initial rifting along the Tethys Sea formed a northern continental mass, Laurasia, and a southern continental mass, Gondwanaland. Then plate movements caused North American and Eurasian separation coincidentally with the separation of South America, Africa, and India. Australia and Antarctica were the last to separate. The major plates are named after the dominant geographic feature on them such as the North American and South American plates. Plate motions are believed to have transported large crustal blocks several thousand miles, suturing very different terrains together after collision with a larger mass. These "exotic" terrains may include segments of island arcs quite unrelated to the history of the continent onto which they are sutured. Some geologists believe that continents grow in size primarily by the addition of exotic terrains.

(Reference: http://education.yahoo.com/reference/encyclopedia/entry?id=37723)

**Platform:** A relatively flat, nearly level area of sedimentary rocks in a continent that overlies or abuts the basement rocks of a craton.

(Reference: http://www.glossary.oilfield.slb.com/Display.cfm?Term=platform)

**Polar cap absorption events (PCAs):** PCAs are attributed to high energy protons which escape from the Sun when large flares occur and move along the earth’s magnetic field lines to the polar regions. There they ionize the D region, causing attenuation of HF waves passing through the polar D region. PCAs are most likely to occur around solar maximum, however, they are not as frequent as short wave fade-outs.

- PCAs may commence as soon as 10 minutes after the solar flare and last for up to 10 days;
- the effects of PCAs can sometimes be overcome by relaying messages on circuits which do not require polar refraction points;
- even the winter polar zone (a region of darkness) can suffer the effects of PCAs. The particles from the Sun may actually produce a night D region.

(Reference: http://www.wulfden.org/NVQS/PropStuff/INTROHFP.HTM.)

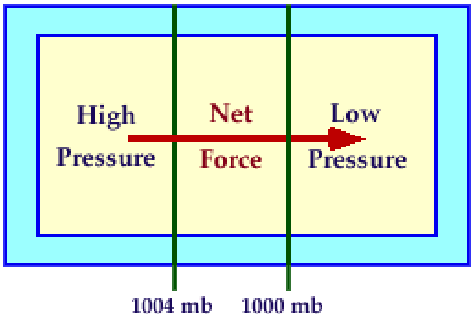
**Potential:** 1. A function of space, the gradient of which is equal to a force.

In symbols,

$$\mathbf{F} = -\nabla\varphi,$$

where **F** is the force, ∇ the del operator (see del operator), and φ the potential. A force that may be so expressed is said to be “conservative,” and the work done against it in motion from one given equipotential surface to another is independent of the path of the motion. In meteorology, the force of gravity has a potential, the geopotential, which, if the acceleration of gravity *g* is taken as constant, may be written $\varphi = gZ$, where *Z* is the height coordinate. The pressure force has in general no potential, nor do the Coriolis or viscous forces. By extension and analogy, the velocity potential, acceleration potential, and Gibbs function (thermodynamic potential) are defined. 2. Applied to the value that an atmospheric thermodynamic variable would attain if processed adiabatically from its initial pressure to a standard pressure, typically 100 kPa.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=potential1)

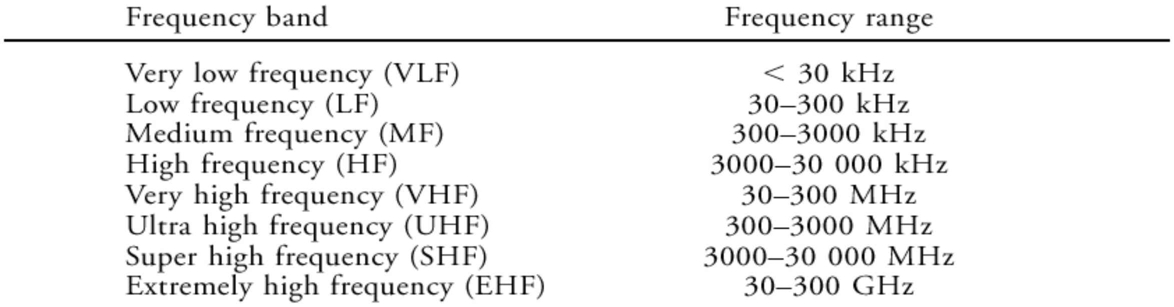
**Pressure Gradient Force:** Directed from high to low pressure The change in pressure measured across a given distance is called a "pressure gradient".



The pressure gradient results in a net force that is directed from high to low pressure and this force is called the "pressure gradient force".
(Reference:
http://ww2010.atmos.uiuc.edu/(Gh)/wwhlpr/pressure_gradient.rxml?hret=/guides/mtr/fw/geos.rxml)

**Radiation:** 1. The process by which electromagnetic radiation is propagated through free space. The propagation takes place at the speed of light ($3.00 \times 10^8$ m $s^{-1}$ in vacuum) by way of joint (orthogonal) oscillations in the electric and magnetic fields. This process is to be distinguished from other forms of energy transfer such as conduction and convection. 2. Propagation of energy by any physical quantity governed by a wave equation. 3. See alpha ray, beta ray.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=radiation1)

**Radio frequency band:** A specified range of frequencies of electromagnetic waves.
Radio frequency bands are classified as follows.



| Frequency band | Frequency range |
|---|---|
| Very low frequency (VLF) | < 30 kHz |
| Low frequency (LF) | 30–300 kHz |
| Medium frequency (MF) | 300–3000 kHz |
| High frequency (HF) | 3000–30 000 kHz |
| Very high frequency (VHF) | 30–300 MHz |
| Ultra high frequency (UHF) | 300–3000 MHz |
| Super high frequency (SHF) | 3000–30 000 MHz |
| Extremely high frequency (EHF) | 30–300 GHz |

These bands, based on multiples of 3, are a consequence of the speed of light being very nearly equal to 3 x $10^8$ m $s^{-1}$. Thus, VHF corresponds to free-space wavelengths 1–10 m and so on.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=radio-frequency-band1)

**Radio-frequency Heating:** In radio-frequency heating, high-frequency waves are generated by electromagnetic oscillators. If the waves have a particular frequency (or wavelength), their energy can be transferred to the charged particles in the plasma, which in turn collide with other plasma particles, thus increasing the temperature of the bulk plasma.
(Reference: http://www.pppl.gov/fusion_basics/pages/plasma_heating.html)

**Re** = earth radius = 6,378 km = 3,986 miles.

**Return stroke:** The intense luminosity that propagates upward from earth to cloud base in the last phase of each lightning stroke of a cloud-to-ground discharge. In a typical flash, the first return stroke ascends as soon as the descending stepped leader makes electrical contact with the earth, often aided by short ascending ground streamers. The second and all subsequent return strokes differ only in that they are initiated by a dart leader and not a stepped leader. It is the return stroke that produces almost all of the luminosity and charge transfer in most cloud-to-ground strokes. Its great speed of ascent (about $1 \times 10^8$ m $s^{-1}$) is made possible by residual ionization of the lightning channel remaining from passage of the immediately preceding leader, and this speed is enhanced by the convergent nature of the electric field in which channel electrons are drawn down toward the ascending tip in the region of the streamer's electron avalanche. Current peaks as high as $3 \times 10^5$ A have been reported, and values of $3 \times 10^4$ A are fairly typical. The entire process of the return stroke is completed in a few tens of microseconds, and even most of this is spent in a long decay period following an early rapid rise to full current value in only a few microseconds. Both the current and propagation speed decrease with height. In negative cloud-to-ground flashes the return stroke deposits the positive charge of several coulombs on the preceding negative leader channel, thus charging earth negatively. In positive cloud-to-ground flashes, the return stroke deposits the negative charge of several tens of coulombs on the preceding positive leader channel, thus increasing positive charge on the ground. In negative cloud-to-ground flashes, multiple return strokes are common. Positive cloud-to-ground flashes, in contrast, typically have only one return stroke. The return streamer of cloud-to-ground discharges is so intense because of the high electrical conductivity of the ground, and hence this type of streamer is not to be found in air discharges, cloud discharges, or cloud-to-cloud discharges.

Hagenguth, J. H., 1951: Compendium of Meteorology, 137–141.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=return-stroke1)

**Ring current:** The ring current consists of geomagnetically trapped 10 - 200 keV ions (mainly $H^+$, $He^+$, and $O^+$) and electrons that drift azimuthally around the earth at radial distances of about 2-7 Re, overlapping the radiation (van Allen) belt region. The drift is a combined curvature and gradient drift which is eastward for electrons and westward for ions, i.e., the direction of the current is westward. (Reference: http://www.oulu.fi/~spaceweb/textbook/ring_current.html.)

**Rossby waves:** Rossby (or planetary) waves are large-scale motions in the ocean or atmosphere whose restoring force is the variation in Coriolis effect with latitude. The waves were first identified in the atmosphere in the 1940s by Carl-Gustaf Arvid Rossby who went on to explain their motion. (Reference: http://www.free-definition.com/Rossby-wave.html.)

**Scalar:** Any physical quantity with a field that can be described by a single numerical value at each point in space. A scalar quantity is distinguished from a vector quantity by the fact that a scalar quantity possesses only magnitude, whereas a vector quantity possesses both magnitude and direction. Thus, pressure is a scalar quantity and velocity is a vector quantity.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=scalar1)

**Seafloor spreading:** Theory of lithospheric evolution that holds that the ocean floors are spreading outward from vast underwater ridges. First proposed in the early 1960s by the American geologist Harry H. Hess, its major tenets gave great support to the theory of continental drift and provided a conceptual base for the development of plate tectonics.

Discovery of the Mid-Ocean Ridges

Development of highly sophisticated seismic recorders and precision depth recorders in the 1950s led to the discovery in the early 1960s that the Mid-Atlantic Ridge, a vast, sinuous undersea mountain chain bisecting the Atlantic Ocean, was in fact only a small segment of a globe-girdling undersea mountain system some 40,000 miles (64,000 km) in length. In many locations, this mid-ocean ridge was found to contain a gigantic cleft, or rift, 20 to 30 miles (32—48 km) wide and c.1 mile (1.6 km) deep, extending along the crest of the ridge. The ridge itself does not form a smooth path, but is instead offset in many places. The offsets are called fracture zones, or transform faults. The ridge crest and its associated transform faults are the locus of nearly all shallow earthquakes occurring in mid-ocean areas. Continued study of the mid-ocean ridges is a major component of U.S. research in the global oceans.

Role of the Spreading Center

In 1962 Hess proposed that the seafloor was created at mid-ocean ridges, spreading in both directions from the ridge system. At the spreading center, liquid rock called basaltic magma rises from the earth’s mantle as it upwells beneath the spreading axis. When the magma hardens, it forms new oceanic crust that becomes welded to the original crust. Spreading is believed to be caused by far-field stresses, and the upwelling of the mantle beneath the spreading axis is the passive response to plate separation. The oceanic trenches bordering the continents mark regions where the oldest oceanic crust is reabsorbed into the mantle through steeply inclined, earthquake-prone subduction zones. The pull of the deeply plunging lithosphere is one of the forces that may drive plate separation.

Supporting Evidence for Seafloor Spreading

Abundant evidence supports the major contentions of the seafloor-spreading theory. First, samples of the deep ocean floor show that basaltic oceanic crust and overlying sediment become progressively younger as the mid-ocean ridge is approached, and the sediment cover is thinner near the ridge. Second, the rock making up the ocean floor is considerably younger than the continents, with no samples found over 200 million years old, as contrasted with maximum ages of over 3 billion years for the continental rocks. This confirms that older ocean crust has been reabsorbed in ocean trench systems.

By the mid-1960s studies of the earth’s magnetic field showed a history of periodic reversals in polarity (see paleomagnetism). A timescale for "normal" and "reversed" polarity was established, showing 171 magnetic "flip-flops" in the past 76 million years. Magnetic surveys conducted near the mid-ocean ridge

showed elongated patterns of normal and reversed polarity of the ocean floor in bands paralleling the rift and symmetrically distributed as mirror images on either side of it. The magnetic history of the earth is thus recorded in the spreading ocean floors as in a very slow magnetic tape recording, forming a continuous record of the movement of the ocean floors. Other supportive evidence has emerged from study of the fracture zones that offset the sections of the ridge.
(Reference: http://education.yahoo.com/reference/encyclopedia/entry?id=42626)

**Schumann resonance:** Electromagnetic waves in the extremely low frequency (ELF) range trapped in the spherical cavity formed by the conductive earth and the conductive ionosphere. The fundamental resonance mode represents one wavelength around the earth with a corresponding frequency of approximately 7.8 Hz. Other higher order frequency modes frequently discernible are 14, 20, 26, 33, 39, and 45 Hz with slight diurnal variation. The resonances are maintained continuously by global lightning activity.
(Reference: http://www.oulu.fi/~spaceweb/textbook/schumann.html.)

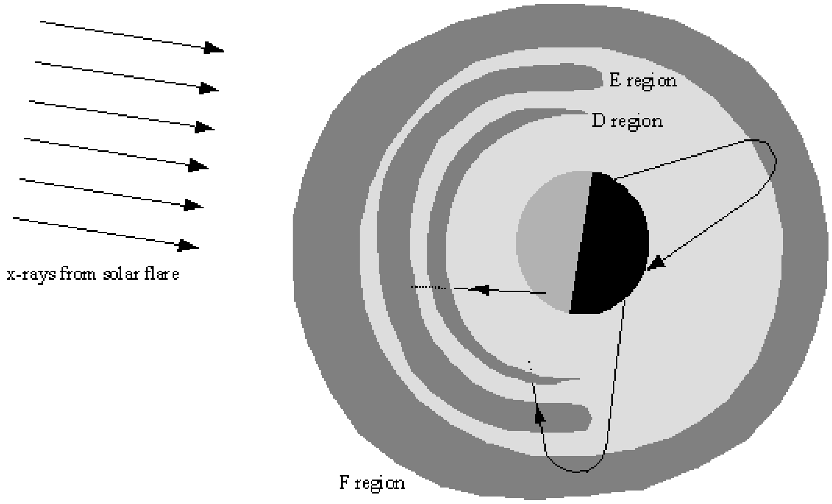
**Seismology:** Scientific study of earthquakes and related phenomena, including the propagation of waves and shocks on or within the earth by natural or artificially generated seismic signals.
Seismographic Instruments
Instruments used to detect and record seismic disturbances are known as seismographs. Those in use today vary somewhat in design and function, but generally a heavy mass, either a pendulum or a large permanent magnet, is connected to a mechanical or optical recording device. When earthquake tremors occur, the pendulum or the magnet, because of inertia, remains still as the earth moves beneath, with the relative motion between the earth and the instrument magnified mainly by electrical amplifying apparatus. The graphic record, called the seismogram, can be used to establish information about an earthquake, e.g., its severity and distance. By using three instruments, each set to respond to motions from a different direction (north-south horizontal, east-west horizontal, and vertical), both the distance and the direction of the earth movement can be determined. Three or more widely spaced seismographic stations are required to pinpoint the location of earthquakes in remote regions.
Although seismographs have been used since their invention by John Milne in 1880, until the end of the 20th century their placement was limited to land areas, creating conspicuous gaps in global seismic coverage under the oceans that cover most of the earth’s surface. During the late 1990s geologists began to create an underwater network of geological observatories using undersea coaxial cables no longer used for communications. This enabled the more precise detection and measurement of seismic disturbances occurring between the continental land masses.
Development of Seismology
The American scientist John Winthrop (1714—79), often called the founder of seismology, was one of the first to make scientific studies of earthquakes. By analyzing seismic data from a 1909 earthquake near Zagreb (now in Croatia), the Austro-Hungarian meteorologist Andrija Mohorovičić discovered a boundary between the crust and mantle, now called the Mohorovičić discontinuity or Moho. Seismological studies were furthered by the U.S. seismologist Charles F. Richter, who invented the Richter scale to determine an earthquake's magnitude. Each successive point on the logarithmic scale represents an increase by a factor of 10 in wave amplitude. A modified Mercalli scale, originally developed by the Italian seismologist Giuseppe Mercalli, is also based on the earthquake's effects on the surface.
Applications of Seismology
One aspect of seismology is concerned with measuring the speeds at which seismic waves travel through the earth. Past earthquake studies have shown that P, or primary/compressional, waves travel fastest through the earth; S, or secondary/transverse, waves cannot pass through liquids, allowing scientists to

discern the earth’s many boundary layers known as the crust, mantle, and core. For example, the disappearance of S waves below 1,800 miles (2,900 km) shows that the outer core of the earth is liquid. Seismologists also prepare seismic risk maps for earthquake-prone countries; these indicate the degree of seismic danger. In addition, seismologists use earthquake data to determine plate boundaries (see plate tectonics); active earthquake areas generally coincide with plate margins, both destructive and growing, and transform faults.

An important commercial application of seismology is its use in prospecting for oil deposits. The first oil field to be discovered by this method was found in Texas in 1924. A portable seismograph is set up in the area to be investigated, and an explosive energy source is activated nearby; formerly, explosives such as dynamite were used to create the seismic waves, but they have been largely replaced by high-energy vibrators on land and air-gun arrays at sea. The waves generated are received by detectors known as geophones; on land, these are commonly placed in a fan-shaped pattern on the ground. From an interpretation of the waves created by the energy source and recorded by the seismograph, the detection of geological structures in which oil may be trapped is possible. Seismic methods are sometimes used to locate subsurface water and to detect the underlying structure of the oceanic and continental crust. With the development of underground testing of nuclear devices, seismographic stations for their detection were set up throughout the world.

(Reference: http://education.yahoo.com/reference/encyclopedia/entry?id=42775)

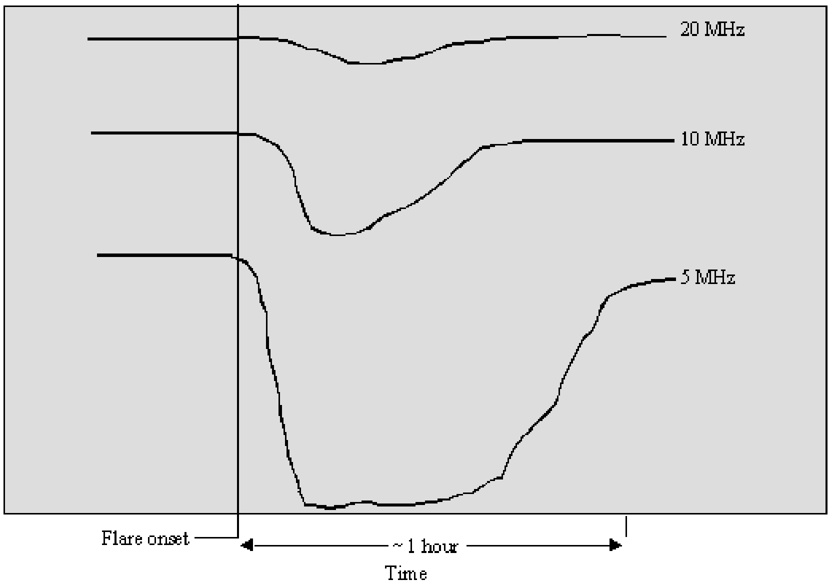
**Short wave fade-outs (SWFs):** Also called daylight fade-outs or sudden ionospheric disturbances (SIDs). Radiation from the Sun during large solar flares causes increased ionization in the D region of the ionosphere which results in greater absorption of HF radio waves, see Figure 1 below. If the flare is large enough, the whole of the HF spectrum can be rendered unusable for a period of time. Fade-outs are more likely to occur around solar maximum and in the first part of the decline to solar minimum.



Fade-outs affect only those circuits where the wave passes through the D region. That is, circuits with daytime sectors. Night circuits are unaffected by fade-outs.

The main features of SWFs are:

- only circuits with daylight sectors will be affected;
- fade-outs usually last from a few minutes to sometimes two hours, with a fast onset and a slower recovery. The duration of the fade-out will depend on the intensity and duration of the flare;
- the magnitude of the fade-out will depend on the size of the flare and the position of the Sun relative to the point where the radio wave passes through the D region. The higher the Sun with respect to that point, the greater the amount of absorption;
- absorption is greatest at lower frequencies, which are the first to be affected and the last to recover. Higher frequencies are normally less affected and may still be usable, see Figure 2.



Fade-outs affect lower frequencies first and these are the last to recover.
Higher frequencies are least affected and with many fade-outs will be unaffected.

(Reference: http://www.wulfden.org/NVQS/PropStuff/INTROHFP.HTM)

**Solar wind:** The concept of continuous solar wind developed in 1950's. First, Biermann (1951, 1957) observed comet tails as they passed close to the Sun, and explained the observed tail deflection by a continuous flux of protons from the Sun. Then Parker (1959) showed that the solar corona must expand, and called the outward streaming coronal gas 'solar wind'.

The outermost region of the Sun, corona, is indeed very hot, so hot that the hydrogen and helium can escape gravitational attraction and form a steadily streaming outflow of material called the solar wind. Because of its high temperature and constant illumination by the Sun, solar wind is fully ionized plasma. Furthermore, because of the heating, compression, and subsequent expansion, the solar wind becomes supersonic above a few solar radii. At Mercury, the solar wind Mach number is about 3, while at the outer planets, Mach number can be 8 and above.

The expanding solar wind drags also the solar magnetic field outward, forming what is called the interplanetary magnetic field (IMF). The region of space in which this solar magnetic field is dominant is called the heliosphere. Although the solar wind moves out almost radially from the Sun, the rotation of the Sun gives the magnetic field a spiral form (garden hose effect). At the orbit of the earth the angle between the field lines and the radial is about 45 degrees. Furthermore, sectors (typically four) with alternating inward and outward directed magnetic fields can be identified.

*Characteristics*

| Parameter | Minimum | Average | Maximum |
|---|---|---|---|
| Flux ($cm^{-2}s^{-1}$) | 1 | 3 | 100 |
| Velocity (km/s) | 200 | 400 | 900 |
| Density ($cm^{-3}$) | 0.4 | 6.5 | 100 |
| Helium % | 0 | 5 | 25 |
| B (nT) | 0.2 | 6 | 80 |

The solar wind plasma consists primarily of hot electrons and protons with a minor fraction of $He^{2+}$ ions and some other heavier ions (typically at high charge states). The table on the right lists the basic solar wind characteristics.
The solar wind originating from the streamers (closed field lines) is slow, while that originating from the coronal holes ("dark" coronal regions of the Sun with open magnetic field structure).is fast. This creates the so-called "co-rotating interaction regions" (CIR) in the interplanetary space. As the solar wind moves away from the sun, tangential discontinuities and interplanetary (fast) shocks are formed, creating pressure variations.
In addition, the variables shown in the table are functions of solar latitude: for example, density is at maximum, speed at minimum around the equator. However, the hemispheres are not exactly symmetric. Typical periodicities in the solar wind can be divided into those that reflect the time scales of the solar processes themselves, those that reflect the rotation of the Sun, and those that reflect the orientation of earth (the most typical observation point) with respect to the Sun. The first include the 11- and 22-year solar cycles and the 1.3 year and 154 day cycles.

*Scale sizes*
The scale sizes of solar wind/IMF structures are typically smaller than the extent of the earth's magnetosphere (about 40 Re). Collier et al. (AFU Fall Meeting 1998) suggest that IMF has two length scales. The first is a few tens of earth's radius and represents the scale over which changes in magnetic field lines are observed at multiple satellites. The second scale length, of the order of a couple hundred Re, may present the characteristic radius of curvature in IMF structures.

*Effects on earth and other planets*
All planets are surrounded by the hot, magnetized, supersonic collisionless solar wind plasma capable of conducting electric current and carrying a large amount of kinetic and electrical energy. Due to the supersonic nature of the solar wind, shock waves are formed in front of the planets (see magnetosphere). Some of the solar wind energy finds its way into the earth's magnetosphere, ionosphere and atmosphere, and

- drives the magnetospheric convection system and energizes much of the plasma on the earth's magnetic field lines
- drives field line resonances and other geomagnetic pulsations
- creates geomagnetic activity
- heats the polar upper atmosphere
- drives large neutral atmospheric winds

Because of these effects, the changes in the solar wind plasma parameters (density, velocity, etc.) and IMF (especially direction in relation to earth's own field) are very important for magnetospheric and ionospheric physics, and the scientific community tries to have continuous monitoring of these parameters via satellites like IMP-8, ISEE, and Wind. However, there are difficulties, because there is - at any given time - at most two or three satellite within the solar wind (quite often none at all), and the solar wind/IMF system is not homogenous, as discussed above.

*Solar wind event categories*

Changes in solar wind characteristics, so called 'solar wind events', can be categorized in several groups (see, e.g., ISTP Solar Wind Catalog and table below).
(Reference: http://www.oulu.fi/~spaceweb/textbook/solarwind.html.)

| Solar wind event categories | |
|---|---|
| **Code** | **Description** |
| **BzN** | Strong northward Bz for extended period |
| **BzS** | Strong southward Bz for extended period |
| **CME** | Coronal Mass Ejections |
| **EyC** | Change in **E**y=**V**x**B**z |
| **HSS** | Very high speed stream for extended period |
| **IMC** | Interplanetary magnetic cloud |
| **IR** | Interaction Region |
| **IS** | Interplanetary shock |
| **LSS** | Very low speed stream for extended period |
| **MISC** | Miscallaneous |
| **PC** | Pressure change |
| **SBC** | Interplanetary sector boundary crossings |

Additional References:

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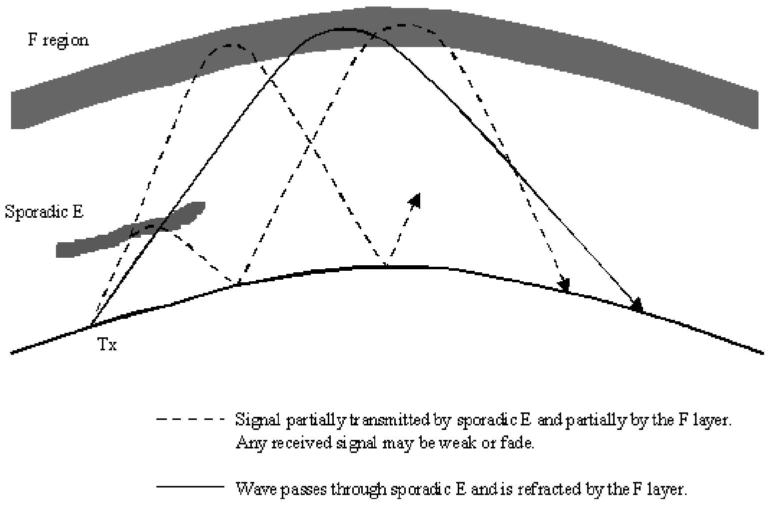
- Russell, C. T., G. L. Siscoe, and E. J. Smith, Comparison of ISEE-1 and -3 interplanetary magnetic field observations, *Geophys. Res. Lett., 7*, 381-384, 1980.

**Solar wind pressure pulses:** The solar wind pressure variations are associated either with tangential discontinuities or interplanetary shocks, which are intrinsic to the solar wind, or with foreshock pressure pulses generated at the bow shock. The pressure pulses have an important role in the solar wind - magnetosphere - ionosphere coupling. They compress the magnetopause, enhance magnetospheric magnetic field strength, and excite resonant azimuthal (vertical) magnetic field oscillations. The ground-based signatures of the pressure pulses are divided into two groups: 1) low-latitude magnetometers record sudden impulse/sudden storm commencement (SI/SSC) signatures as simple step function increases (or decreases) in the H component of the geomagnetic field; 2) high-latitude magnetometers record bipolar signatures in the H component of the geomagnetic field (called traveling convection vortices). (Reference: http://www.oulu.fi/~spaceweb/textbook/pressure_pulses.html.)

**Sporadic E**: Sporadic E may form at any time. It occurs at altitudes between 90 to 140 km (56 to 88 miles) in the E region of the ionosphere, and may be spread over a large area or be confined to a small region. It is difficult to know where and when it will occur and how long it will persist. Sporadic E can have a comparable electron density to the F region, implying that it can refract comparable frequencies to the F region. Sporadic E can therefore be used for HF communications on higher frequencies than would be used for normal E layer communications at times. Sometimes a sporadic E layer is transparent and allows most of the radio wave to pass through it to the F region, however, at other times the sporadic E layer obscures the F region totally and the signal does not reach the receiver (sporadic E blanketing). If the sporadic E layer is partially transparent, the radio wave is likely to be refracted at times from the F region and at other times from the sporadic E. This may lead to partial transmission of the signal or fading.



Some possible paths when sporadic E is present.
(Reference: http://www.wulfden.org/NVQS/PropStuff/INTROHFP.HTM)

**Spread F:** Spread F occurs when the F region of the ionosphere becomes diffuse due to irregularities in that region which scatter the radio wave. The received signal is the superposition of a number of waves refracted from different heights and locations in the ionosphere at slightly different times. At low latitudes, spread F occurs mostly during the night hours and around the equinoxes. At mid-latitudes,

spread F is less likely to occur than at low and high latitudes. Here it is more likely to occur at night and in winter. At latitudes greater than about 40 degrees, spread F tends to be a night time phenomenon, appearing mostly around the equinoxes, while around the magnetic poles, spread F is often observed both day and night. At all latitudes there is a tendency for spread F to occur when there is a decrease in F region frequencies. That is, spread F is often associated with ionospheric storms (see that definition).
(Reference: http://www.wulfden.org/NVQS/PropStuff/INTROHFP.HTM)

**Stepped leader:** The initial leader of a lightning discharge; an intermittently advancing column of high ionization and charge that establishes the channel for a first return stroke.
The peculiar characteristic of this type of leader is its stepwise growth at intervals of about 50– 100 μs. The velocity of growth during the brief intervals of advance, each only about 1 μs in duration, is quite high (about $5 \times 10^7$ m $s^{-1}$), but the long stationary phases reduce its effective speed to only about $5 \times 10^5$ m $s^{-1}$. To help explain its mode of advance, the concept of a pilot streamer was originally suggested, but has been supplanted by analogy to recent work on long laboratory sparks.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=stepped-leader1)

**Stratosphere:** The stratosphere is the layer of earth's atmosphere which, at the equator, is situated between about 17 km and 50 km (11 miles and 31 miles) altitude above the surface, while at the poles it starts at about 8 km (5 miles) altitude due to the lower tropopause height caused by the lower tropospheric temperature there. The stratosphere sits directly above the troposphere and directly below the mesosphere. Within this layer, temperature increases as altitude increases; the top of the stratosphere has a temperature of about 270°K. This top is called the stratopause, above which temperature again decreases with height. The stratosphere is a region of intense interactions among radiative, dynamical, and chemical processes, in which horizontal mixing of gaseous components proceeds much more rapidly that vertical mixing. The stratosphere is warmer than the upper troposphere, primarily because of a stratospheric ozone layer that absorbs solar ultraviolet radiation. An interesting feature of stratospheric circulation is the quasi-Biennial Oscillation (QBO) in the tropical latitudes, which is driven by gravity waves that are convectively generated in the troposphere. The QBO induces a secondary circulation that is important for the global stratospheric transport of tracers such as ozone or water vapor. In northern hemispheric winter, sudden stratospheric warmings can often be observed which are caused by the absorption of Rossby waves in the stratosphere.
(Reference: http://www.free-definition.com/Stratosphere.html.)

**Streak lightning:** Ordinary lightning, of a cloud-to-ground discharge, that appears to be entirely concentrated in a single, relatively straight lightning channel. Compare forked lightning, zigzag lightning.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=streak-lightning1)

**Sun-aligned arcs:** Sun-aligned arcs are auroral features found within the polar cap, as opposed to the auroral oval where the more typical arcs reside. The first global image of this phenomenon was reported by Frank et al. (1982); it consists of luminous belt reaching across the polar cap from noon to midnight (that is why it is also called theta aurora; terms transpolar or polar cap arc are also known). However, first visual observations of such features were by the British Antarctic Expedition already during the austral winter of 1908 (Mawson, 1916). Similarly, first ground-based all-sky-camera observations originate from the International Geophysical Year (IGY) of 1957-1958.
(Reference: http://www.oulu.fi/~spaceweb/textbook/aurora/arc/sun-aligned.html.)

**Thermosphere:** The thermosphere is that layer, of the earth’s atmosphere, which is directly above the mesosphere and directly below the exosphere. Within this layer, ultraviolet radiation causes ionization (see atmosphere). The thermosphere, from the Greek thermo for heat, begins about 80 km (50 miles) above the earth. At these high altitudes, the residual atmospheric gases sort into strata according to molecular mass. Thermospheric temperatures increase with altitude due to absorption of highly energetic solar radiation by the small amount of residual oxygen still present. Temperatures can rise to 2,000°C. Radiation causes the scattered air particles in this layer to become charged electrically, enabling radio waves to bounce off and be received beyond the horizon. At the exosphere, beginning at 500 to 1,000 km (313 to 625 miles) above the earth’s surface, the atmosphere blends into space. The few particles of gas here can reach 2,500°C (4,500°F) during the day.
(Reference: http://www.free-definition.com/Thermosphere.html.)

**Torque:** The moment of a force about a given point; that is, the vector product of the position vector (from the given point to the point at which the force is applied) and the force.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=torque1)

**Troposphere:** The troposphere is the lowermost portion of earth’s atmosphere and the one in which clouds and most other weather phenomena occur. This layer extends to an altitude of 16-18 km (10-11 miles) over tropical regions, decreasing to less than 10 km (6 miles) over the poles, and contains approximately 80% of the total air mass. Generally, jets fly near the top of this layer. The troposphere is directly below the stratosphere. The troposphere is divided into six zonal flow regions, called cells. These are responsible for atmospheric circulation, and produce the prevailing winds. The word troposphere stems from the Greek "tropos" for "turning" or "mixing". This region, constantly in motion, is the densest layer. Nitrogen and oxygen are the primary gases within this region. The change of temperature with height is larger than in other layers, the temperature decreasing with altitude. The tropopause marks the limit of the troposphere and the beginning of the stratosphere. The temperature above the tropopause increases slowly with height up to about 50 km (31 miles).
(Reference: http://www.free-definition.com/Troposphere.html.)

**Universal Time (UT):** The times of various events, particularly astronomical and weather phenomena, are often given in "Universal Time" (abbreviated UT) which is sometimes referred to, now colloquially, as "Greenwich Mean Time" (abbreviated GMT). The two terms are often used loosely to refer to time kept on the Greenwich meridian (longitude zero), five hours ahead of Eastern Standard Time. Times given in UT are almost always given in terms of a 24-hour clock. Thus, 14:42 (often written simply 1442) is 2:42 p.m., and 21:17 (2117) is 9:17 p.m. Sometimes a Z is appended to a time to indicate UT, as in 0935Z.
(Reference: http://aa.usno.navy.mil/faq/docs/UT.html)

**Van Allen belts:** The Van Allen radiation belts are high-energy solar wind and cosmic radiation particles trapped by the magnetic field of the earth. The Van Allen radiation belt is a torus of energetic charged particles around earth, trapped by earth’s magnetic field. When the belts "overload", particles strike the upper atmosphere and fluoresce, causing the polar aurora. The presence of a radiation belt had been theorized prior to the Space Age and the belt's presence was confirmed by the Explorer I on January 31, 1958 and Explorer III missions, under Doctor James van Allen. The trapped radiation was first mapped out by Explorer IV and Pioneer III. Qualitatively, it is useful to view this belt as consisting of two belts around earth, the inner radiation belt and the outer radiation belt. The particles are distributed such that the inner belt consists mostly of protons while the outer belt consists mostly of electrons. The outer belt is centered about 18,000 km (11,250 miles) above the equator and the inner more energetic belt

is centered at 3000 km (1,875 miles). Within these belts are particles capable of penetrating ~1g/cm2 of shielding (1 millimeter of lead). The term Van Allen belts refers specifically to the radiation belts surrounding earth; however, similar radiation belts have been discovered around other planets. The Sun does not support long-term radiation belts. The atmosphere limits the belts' particles to regions above 200-1000 km (125-625 miles), while the belts do not extend past 7 Re. The belts are confined to an area which extends about 65° from the celestial equator.
(Reference: http://www.free-definition.com/Van-Allen-radiation-belt.html.)

**Vector:** Any quantity, such as force, velocity, or acceleration, that has both magnitude and direction at each point in space, as opposed to a scalar that has magnitude only. Such a quantity may be represented geometrically by an arrow of length proportional to its magnitude, pointing in the assigned direction. A unit vector is a vector of unit length; in particular, the three unit vectors along the positive $x$, $y$, and $z$ axes of rectangular Cartesian coordinates are denoted, respectively, by **i**, **j**, and **k**. Any vector **A** can be represented in terms of its components $a_1$, $a_2$, and $a_3$ along the coordinate axes $x$, $y$, and $z$, respectively; for example, $A = a_1\mathbf{i} + a_2\mathbf{j} + a_3\,\mathbf{k}$. A vector drawn from a fixed origin to a given point $(x, y, z)$ is called a position vector and is usually symbolized by **r**; in rectangular Cartesian coordinates,

$$\mathbf{r} = x\mathbf{i} + y\mathbf{j} + z\mathbf{k}.$$

Equations written in vector form are valid in any coordinate system. Mathematically, a vector is a single-row or single-column array of functions obeying certain laws of transformation.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=vector1)

**Zigzag lightning:** Ordinary lightning of a cloud-to-ground discharge that appears to have a single, but very irregular, lightning channel. Compare streak lightning, forked lightning.
(Reference: http://amsglossary.allenpress.com/glossary/search?id=zigzag-lightning1)