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WINDS in th

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THE EVIDENCE for the existence of winds in the ionosphere is now manifold. It is partly directly visual, from the motion of luminous meteor trails and high luminous night clouds and patchiness in the night airglow. It is partly based on inference from indirect observations, such as the geomagnetic variations at the earth's surface; these are ascribed to electric currents partly flowing in the ionosphere, which are explained by dynamo action of ionospheric motions. Another type of indirect observational evidence is provided by the scintillation of radio stars. The most abundant and varied evidence, however, is afforded by inference from observations in which human experiment also plays a vital part, namely by the transmission of radio beams to the ionosphere and their reception after they have been modified by passage through that region, either solely by the influence of ionospheric motion, or by the fleeting presence there of ionized meteor trails.

From all this evidence it appears that the ionosphere is a region even more dynamic than the atmosphere in whose winds we daily live and sail and fly.

The Lower Atmosphere

One can imagine the problem of the earth's lower atmosphere being presented to a learned and accomplished mathematical physicist living on another celestial body, under conditions quite different from those we know. Suppose him to be fully aware of the general laws of Nature and of the physical and chemical properties of matter. The relevant astronomical information about the earth, sun and moon—their masses, sizes, relative orientations, rotations and orbital motions, the nature and changes of the sun's wave and corpuscular radiations, the details of the earth's land and liquid surface and heat flow to it from the interior—are supposed all specified in full: so also are the total mass of the air and its division between the various elementary and compound gases. From all this he is expected to infer deductively the actual phenomena of our lower atmosphere.

Certainly one can marvel at the immensity of the task confronting him, and wonder how he would gradually bring to light all the varied atmospheric phenomena—the different layers and belts of the atmosphere, the general circulations, the trade and other wind systems, the larger weather features of cyclonic and anticyclonic areas, the topographical winds, the land and sea breezes, the detailed turbulence, the manifold clouds (besides those of the troposphere, the mother-of-pearl clouds of the stratosphere), thundercloud systems and lightning, monsoons, tornadoes, jet streams, rain and snow and hail and ice, and much more.

The difficulty of the task, as judged by our human intellectual standards, is clear from this: that although we *know from observation* a multitude of these consequences, we are still unable in many cases to deduce them from the initial data. This is indeed partly due to lack of some of the data—concerning some gaseous and atomic and molecular properties, especially those connected with the emission and absorption of radiation. But where this does not hamper us, we are still as yet unable to explain even many of the *interconnections* between the observed phenomena. The main reason is their extreme complexity, and our limited present ability to formulate and solve the associated mathematical equations.

If this be so for the lower atmosphere, how much more true must and will it be for the ionosphere—which is not only dynamically more active, but also more complex in many ways? Moreover our knowledge of many general physical properties of the gases there, and of the relevant parts of the solar radiations, is much more deficient than for the lower atmosphere; and our *observational* knowledge of the ionosphere is far inferior to our meteorological knowledge, amassed through generations of increasingly intensive and widespread observation.

Hence our progress towards understanding the ionospheric motions must be slow, and our success in deductive studies is likely in most cases to follow rather than precede that of our observational researches.

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IONOSPHERE

Dynamic Influences Affecting all Regions

In considering the causes of ionospheric movements, we may first notice some dynamic influences common to all atmospheric regions, and then discuss special factors operating in the ionosphere.

One can hardly doubt that throughout the atmosphere the main causes of motion are thermal, depending with different degrees of directness on energy transmitted from the sun, chiefly by wave radiation.

A minor cause is tidal action, principally by the moon, but also by the sun. If the sun and earth grew cold, all the other astronomical facts remaining unaltered, the tidal *forces* would still persist as now; but the tidal motions would be different because the atmosphere on which they would act would have a different structure, with no ozonosphere and no ionosphere distended by dissociation and high temperature. The winds would be purely tidal, and far milder and more regular than those we know. But still, in the lower atmosphere, at least, they would be complicated by the influence of the irregular topography of the land surface, and by the tidal rise and fall of the surface underlying the atmosphere—chiefly by the tides in the oceans, so irregular in outline and depth, but also by the tides of the solid earth. If only the sun grew cold, and the outflow of heat from the earth's interior continued, this very slight thermal flow would then have more than its present very minor relative dynamical influence.

Considering things as they are, the lower atmosphere gains heat from the sun, mainly indirectly. High-temperature radiation to which the air is nearly transparent is absorbed by the land and oceans; much of this energy is then re-emitted by them in the form of radiation at a lower temperature, more subject to absorption by the polyatomic gases present in very small relative amounts in the air—water vapor, carbon dioxide, ozone, nitrous oxide, and so on. These gases are also good *radiators* at the same low temperatures, and take a leading part in the *loss* of heat from the lower atmosphere.

The angle of incidence of the sunlight upon the spherical earth varies daily and seasonally, and is different in different latitudes: though the atmosphere as a whole is in approximate long-term thermal equilibrium, the processes of gain and loss of heat do not balance in each latitude; more heat is gained than lost in some latitudes, and *vice versa* in others. In consequence the air is set in motion on a grand scale, the atmosphere being indeed a large heat engine.

Sir George Simpson's pioneer studies of the atmospheric heat balance in the lower atmosphere were of great value despite the lack of knowledge of some important radiative data concerning water vapor; they have been corrected as later knowledge became available, but their dynamical consequences are not properly worked out. The thermal processes in the *ionosphere* are far less well understood, but when they become better known there will be scope for parallel studies on the over-all heat balance there, and the deviations from it in each latitude. This will then lead on to the investigation of the dynamics of the ionospheric part of the atmospheric heat engine.

Another important dynamical similarity between the lower atmosphere and the ionosphere concerns the deflecting influence of the earth's rotation; its relative importance is even slightly enhanced in the ionosphere by the slight upward decrease of gravity.

At this point I should say that by the *lower* atmosphere I here mean the troposphere and the overlying region up to about 40 kilometers, containing the bulk of the ozone layer, this including the stratosphere and part of the *mesosphere*, the region in which the air temperature T has a peak or maximum. The lower part of the mesosphere, in which (owing to the ozone layer) T increases upwards, I call the *mesoincline*, and the upper part, in which T decreases upwards, to the *mesopause* or level of minimum T, I call the *mesodecline*. Above the mesopause T again increases upwards, apparently at least up to the peak of the F_2 layer; this region I call the *thermosphere*.

Dynamic Influences Varying with Level

Surface Topography. In the lower atmosphere the irregular topography and nonuniform seasonally varying nature of the earth's surface have much influence on the air motions, modifying the general consequences of the varying incidence of sunlight due to the earth's sphericity and rotation. In the ionosphere there is nothing comparable to this boundary influence, so adjacent in the lower atmosphere; but we cannot be quite certain that this low level influence is without appreciable effect on ionospheric dynamics.

Horizontal Oceanic Transfer of Heat. The lower atmosphere is significantly affected thermally and dynamically by the horizontal transfer of heat by ocean currents. Except perhaps at remote second-hand, this also will not influence the ionosphere.

Energy Storage in the Oceans. Processes of energy storage have dynamical importance by influencing the transformations of radiant and other forms of energy into kinetic energy. For the lower atmosphere the thermal storage of the oceans is important, but as in the case of the surface topography and the ocean currents, the heat storage of the oceans has only problematic and diminished importance for the ionosphere.

Latent Heat. In the lower atmosphere water provides an important means of energy storage by the *latent heat* of evaporation. In the ionosphere the amount of water vapor present will be dynamically insignificant, owing to the dissociation of water molecules by sunlight.

Energy of Dissociation, Ionization, and Excitation. In the ionosphere, however, dissociation processes provide a considerable energy storage that is practically absent in the troposphere, though present to a small extent in the ozone layer of the stratosphere and lower mesosphere. Per molecule affected, the energy much exceeds that involved in evaporating or condensing a molecule of water; and in the E region the number of dissociated oxygen atoms forms a much larger fraction of all the air particles there than do the evaporated water molecules in the troposphere. Thus the storage of dissociation energy in the ionosphere probably has great importance for ionospheric dynamics. Smaller amounts of energy storage are afforded by the dissociation of neutral particles into ions, or into ions and electrons. These are relatively long-term forms of storage, the rate of transformation of this energy by recombination being inversely proportional to some power of the density. Excitation of atoms and molecules provides another form of energy storage, but of much shorter term; its rate of transformation into heat energy is likewise greater, the greater the air density.

Transformation of Stored Energy. In the troposphere the release of latent heat and its transformation into actual heat is induced by the *rise* of humid air; as it expands under the reduced pressure, it cools and the water vapor in it may condense, with precipitation in one of its varied forms. In the ionosphere the release of stored energy of dissociation, ionization and excitation is accelerated by the *descent* of air, to regions where the pressure and density are increased.

Heat Conduction. In the lower atmosphere *conduction* of heat, as of momentum, takes place mainly by eddy conduction, through turbulence; the molecular conductivity is relatively insignificant. The molecular conductivity is independent of the density, but increases with the temperature; the influence of heat conduction on the temperature depends on the conductivity divided by the density; hence the importance of molecular conductivity must be increasingly great in the upper levels of the ionosphere.

In the F region of the ionosphere, downward heat conduction provides the chief process of heat loss, according to D. R. Bates, provided that this region is at a high temperature, as generally supposed.

Absorption of Radiation. In the lower atmosphere the incoming solar radiation is little absorbed except by the polyatomic gas ozone, itself produced by the only dissociation process of fundamental importance occurring there (in the stratosphere) namely, that of molecular oxygen; the solar energy absorbed by ozone is transformed into heat partly through the dissociation of ozone itself, which occurs marginally down to the lowest levels.

In the ionosphere the chief absorbers of solar radiation are the diatomic gases—oxygen and nitrogen—and the atoms and ions formed from them by such absorption. Thus the absorbing gases in the ionosphere are main constituents, not rare constituents like ozone in the lower atmosphere.

Emission of Radiation. In the lower atmosphere the loss of energy by low temperature radiation is achieved by emission from the relatively rare polyatomic constituents—water vapor, carbon dioxide, ozone and others. In the F region of the ionosphere D. R. Bates, who has reviewed the relative importance of the various emission possibilities, assigns chief importance to atomic oxygen (one of the major constituents there), through magnetic dipole radiation in a transition between the two low levels of the ground term. Polyatomic constituents are extremely rare in the ionosphere because of the dissociating influence of sunlight.

Friction and Turbulence. In the lower atmosphere there is boundary friction with the earth's surface, and internal friction. Internal friction exists throughout the atmosphere, but in the lower atmosphere its importance is due mainly to turbulence or eddy friction, which there far outweighs molecular friction or viscosity. The dynamical importance of friction, however, depends on the viscosity divided by the density, that is, on the kinematic viscosity. The degree of turbulence in the atmosphere is likely to vary much from level to level and from time to time, as in fact it is known to do in the lower atmosphere. The irregular surface of the earth sets up turbulence when winds blow over it. The atmosphere is rendered unstable also without general winds, by the processes that heat and cool it at different levels.

The gradient of the potential temperature greatly affects the degree of turbulence. The potential temperature generally increases upwards, but except in inversions, the actual temperature decreases upwards in the troposphere, and also in the upper part of the mesosphere—the mesodecline; there turbulence is relatively favored. In the mesoincline and in the thermosphere, where the actual temperature increases upwards, turbulence must be heavily damped; also in the isothermal region or stratosphere it is damped, though less heavily.

Except possibly in the mesodecline, located in the lower part of the ionosphere, eddy friction in the ionosphere may ordinarily be less than in the lower atmosphere; but the upward decrease of density may still give it some importance in the ionosphere. Molecular viscosity, however, is independent of the density; hence the kinematic molecular viscosity steadily increases upwards, and in the E layer it is comparable with the value of the eddy kinematic viscosity in the troposphere; in the thermosphere the supposed high temperature will enhance this effect. In the lower atmosphere, above the first few kilometers, the friction is not very important for the larger-scale motions, and this may also be so in the lower ionosphere; but with increasing height its importance in the ionosphere must steadily increase, until the kinematic viscosity becomes comparable with that of molasses.

External Impact. The lower atmosphere is traversed occasionally by meteorites, but these have no appreciable dynamical influence upon it. The ionosphere is subject on the outside to the impact of solar, interplanetary and interstellar gas, dust and meteors, which may have appreciable though minor dynamic significance—not directly but intermediately, through the conversion of their high relative kinetic energy into atmospheric heat.

Electrostatic Influences. In so far as the gas and dust are ionized, their entry into the ionosphere may set up electrostatic forces of direct dynamic significance, chiefly in auroral regions. Electrostatic fields are also set up (see next paragraph) by the dynamic action of ionospheric movements in the presence of the geomagnetic field.

Electromagnetic Influences. The ionosphere, because of its ionization, differs notably from the lower atmosphere in being greatly influenced by the presence of the geomagnetic field. Throughout the atmosphere the winds generate electromotive forces, owing to the presence of the field, but in the lower atmosphere these forces have little significance. But in the electrically conducting ionosphere they are important because there they can impel electric currents and set up electrical fields, with reactions on the mass motion of the air. On this account the equations governing the motions in the ionosphere are much more complicated than those —already sufficiently intractable—for the lower atmosphere, because they must include additional electrostatic and electromagnetic terms.

Dynamo Action in the Ionosphere. Schuster was the pioneer in the mathematical development of Balfour Stewart's dynamo theory of the daily geomagnetic variations. He recognized that the motion of the air would be mainly horizontal, and that this, in conjunction with the vertical component of the earth's field, would induce horizontal electromotive forces; these would have two results—they would set up an electrostatic charge distribution and field, and impel a system of electric currents flowing horizontally. Any vertical motion of the air across the horizontal component of the earth's field would contribute to the same effects.

The horizontal motion of the air across the horizontal component of the field sets up vertical electromotive forces; these take an important share, only recently recognized, along with the electrostatic field already mentioned, in driving the horizontal electric currents; their action is called electrical drift, and is perpendicular to the direction of the electric force. It is in this way that the inhibiting action of the magnetic field on the motion of charges in directions transverse to the field is largely annulled, restoring the electrical conductivity transverse to the magnetic field almost to the value corresponding to no field.

The effects, however, are not simple, and seem to include the production, during the daytime, over and near the magnetic equator, of a strong enhancement of the electric currents in a rather narrow band or electrojet—the electrical equivalent of a jet stream in meteorology.

These currents i are themselves acted upon by the magnetic field F, with forces $i \times F$ (the vector product), which modify the air motion due primarily to thermal and tidal causes. But it is an imperfect procedure to calculate the currents from the thermal and tidal motions alone, and then try to estimate the modifications in these motions and in the currents due to the electromagnetic forces on the currents; the analysis should be based from the outset upon the full equations containing thermal, tidal and electromagnetic terms.

Even this, however, is not enough; the currents are due to the opposite forces exerted by the magnetic field upon the ions and electrons, when motion is imparted to them by the mass motion of the neutral gas in which they are embedded; the current is a relative diffusion of the positive and negative charges. The magnetic field reacts on this current, that is, on these opposite charges, which are kept from any appreciable bodily separation by their strong mutual electrostatic attraction; this electromagnetic action tends to move the charged constituent of the gas relative to the neutral gas. The neutral gas is partly constrained to share this secondary motion, but in part there is a diffusion of the charged constituent through the neutral air. In the lower ionosphere the two parts of the air mainly move together; in the higher levels the lower air density permits more diffusion. To deal with these effects separate equations, including diffusion terms, must be used for the neutral and charged components of the air—a complication from which the theoretical meteorologist of the lower atmosphere is immune, though he has to consider the diffusion of water vapor through the air.

Radio observations indicate the presence and motions of the electrons; the higher the level, the less certain is it that this motion is the same as that of the main air mass in which the electrons exist.

Turbulence and Electromagnetism. Another feature of this complex situation is concerned with the turbulence superposed on the larger-scale motions. This will produce local irregularities in the induced electric current flow and its magnetic field, and these will generate electrodynamic forces opposing the motion—an electromagnetic damping. Another way of looking at the matter depends on the theorem that in a highly conducting fluid the magnetic tubes of force are carried along with the medium, the more so, the greater the conductivity. Thus the magnetic tubes are tangled up by the turbulence, which creates magnetic energy at the expense of the kinetic energy, until, in the limit, the two forms of energy may in certain circumstances become equal—a process which, as Elsasser has pointed out, may be important also in the very different conditions of turbulence in the earth's liquid metallic core. The radio evidence for considerable ionospheric turbulence, particularly the scintillation evidence during auroral storms, seems likely to imply much local irregularity in the magnetic field there, of which at the ground there will be but little magnetic evidence.

Dynamic Action by External Magnetic Fields. Besides the electrodynamic influences arising within the ionosphere itself, there are probably at times external electrodynamic influences upon it. It is thought that part of the magnetic disturbances experienced at the earth's surface during magnetic storms arises from electric currents located right outside the earth's atmosphere, at a distance of a few earth radii. Their magnetic field will act electrodynamically upon the ionized layers, inducing electric currents in them that partly shield the region below from the external fields and exerting a downward electromagnetic pressure on these currents; the external fields also exert mechanical force on the currents already flowing in the ionosphere, and this force may be either downward or upward. Such a force seems to offer the best hope of explanation of the catastrophic changes observed by Berkner and Wells above Huancayo, Peru, during the outstandingly great magnetic storm of 1938, April 16; twice during that storm the F_2 layer rose rapidly and disappeared, and a new F_2 layer was gradually reformed near its usual level. The upward motion perhaps involved much relative diffusion of the charged component of the air through the neutral component.

Influence of the Lower Atmosphere

Next, I will comment briefly on the possible dynamic influences of the lower atmosphere upon the ionosphere.

Thermal actions in the lower atmosphere frequently produce an unstable condition, which is relieved by vertical interchange of air, despite the general resistance to such vertical motion, whose inhibiting effect was formerly over-emphasized. It is known that portions of tropospheric air near the tropopause become detached as islands in the stratosphere, of different humidity and other properties—the mother-of-pearl clouds sometimes seen may well be visible evidence of such islands. The association of ozone changes and weather systems is another evidence of interconnection between air layers at considerably different heights, and as Sir Charles Normand has recently remarked, those occurring in the autumn, at any rate, when there is little average variation of ozone content with latitude, cannot be explained without vertical motion. Much remains obscure about these interconnections between different levels of the lower atmosphere, but it would seem to me unwise to suppose that they are limited to that region, or to deny the possibility that similar interconnections over a still greater range of height may affect also the ionosphere—as Munro in Australia has suggested.

This open mind on the question, pending more knowledge and understanding, seems to me to be enjoined also by consideration of the strong evidence for an important interconnection between the *tidal* motion of air at low and ionospheric levels. The subject is complex and I can deal only briefly with it here. The main facts to be explained are the unexpectedly large magnitude of the half tidal, half thermal *solar* semidiurnal oscillation of the atmosphere, as revealed by the barometer at ground levels, and of the *lunar* tidal motion in the ionosphere. Kelvin suggested that the former was magnified by resonance, the imposed period of half a solar day nearly coinciding with a free period of similar oscillation of the atmosphere. This proposal has gained substantial confirmation in recent decades, through the work, among others, of Taylor, Pekeris, and Weekes and Wilkes. They have shown that the atmosphere has more than one mode and frequency of free oscillation of tidal type and that the existence and nature of these free oscillations depend greatly on the thermal structure of the whole atmosphere, from the ground upwards to high ionospheric levels. Weekes and Wilkes draw an analogy between the tidal actions of the moon and sun upon the atmosphere, with its alternately hot and cool layers, and electromagnetic propagation in a medium having a variable refractive index; the hot layers—the mesosphere and thermosphere—can act as partial barriers to the upward flow of oscillatory energy due to tidal and thermal action mainly applied in the lower atmosphere; thus the energy of these forced oscillations can be partly trapped and the amplitude built up to a degree not possible in an atmosphere of simpler thermal structure, giving rise to resonance and the observed unexpectedly large oscillations. The associated winds are a minor part of the total wind at all levels investigated, but their comparative theoretical simplicity has enabled theorists to establish the point here emphasized—the possibility, in this case the reality, of external actions that supply energy to the atmosphere mainly at low levels, affecting greatly the air movements at levels a hundred kilometers and more above the ground.

Finally one may note that the properties of the gas of the ionosphere are in many ways so different from those of an ordinary gas that the experience and intuitions of the meteorologist relating to the lower atmosphere may to some extent be misleading in relation to the ionosphere—just as one's ordinary intuition and experience in regard to mechanics may fail us if we handle objects containing hidden gyroscopes.