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STRUCTURE OF THE UPPER LAYERS OF THE ATMOSPHERE

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/Figures are appended./

A. Theory of the Stratosphere

The stratosphere actually begins with the tropopause. This transitional region extending one to 3 kilometers between troposphere and stratosphere is distinguished by special temperature conditions, e.g., temperature inversion. The height of the tropopause depends on geographical latitude, being 16-18 kilometers at the equator and 9-11 kilometers over middle latitudes; it also varies seasonally, being maximum in fall and minimum in spring. The stratosphere is colder (minus 70 to minus 80 degrees centigrade) over the equator than over middle latitudes (minus 45 to minus 55 degrees), and is warmer over the polar regions. The relative positions of stratosphere, tropopause, and troposphere are shown in Figure 1.

Contemporary theory treats the troposphere as a region where temperature is regulated mainly by turbulent mixing and the stratosphere as a region in which it is regulated by radiation heat exchange (radiation equilibrium). The temperature gradient created by the absorption of reradiation is so great that the transfer of warm air from below into colder higher layers causes powerful vertical movements which equalize the temperature. The expansion cooling of air in its upward movement creates the temperature gradient (6 degrees centigrade per kilometer) characteristic of the troposphere. These vertical movements are turbulent, i.e., small and large air bodies mix with each other in their movements. Great progress has been made in the study of atmospheric turbulence by Academician A. N. Kolmogorov and his student, Prof A. M. Obukhov, at the Geophysics Institute, Academy of Sciences USSR. In the stratosphere, however, air temperature does not depend upon vertical mixing but upon radiation equilibrium. Any air mass emits radiation, the amount of which is directly proportional to

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temperature. It also absorbs partially the reradiation passing through it from the earth's surface and radiation of all circumambient air masses. If the energy radiated is greater than that absorbed, then the given air mass will continuously lose its internal energy and will cool or, in the opposite case, heat up. The stable or equilibrium temperature will be that temperature at which the energy radiated is equal to the energy absorbed. The mathematical works of Prof Ye. S. Kuznetsov in the Geophysics Institute, Academy of Sciences USSR, are of great importance in the development of this theory of radiation equilibrium. The methods of solving the equations of radiation energy transfer in absorbing and reflecting media devised by the well-known Soviet astrophysicist V. A. Ambartsumyan (president of the Academy of Sciences Armenian SSR) are highly promising and have won for him a Stalin Prize. The participation of astrophysicists in the solution of such geophysical problems is no accident, for they use the same theory of radiation equilibrium in studying energy conditions in stellar atmospheres.

B. Water Vapor in the Stratosphere

The absorption of radiation energy by various gases in the atmosphere reveals that the less there is of a given gas in the atmosphere, the greater is its absorption. To illustrate, we take the five gases always present in air: nitrogen (78 percent), oxygen (20 percent), water vapor (2 percent), carbon dioxide (0.02 percent), and ozone (0.00003 percent). Nitrogen absorbs no radiation in the infrared, visible, or ultraviolet regions and consequently has no effect on energy processes in the atmosphere. Oxygen absorbs radiation but weakly. The remaining three gases, on the other hand, absorb radiation very actively. Although ozone has recently been studied in detail, the main emphasis has been placed on water vapor throughout almost the entire development of the theory of the stratosphere. Excessive attention to the study of water vapor has become a habit which must be broken by geophysicists. Undoubtedly water vapor does play a very important role in atmospheric processes. It has strong infrared absorption bands and absorbs most of the energy reradiated from the earth, thus influencing greatly the heat balance of the troposphere. Those who developed the theory of radiation equilibrium in the stratosphere assumed that water vapor would also be the main absorbing agent in this region. It has now become clear that the role of water vapor has been overrated and that of other gases underrated.

The amount of water vapor in the upper troposphere and in the stratosphere could not be measured accurately until 1946 for two reasons: (1) at low stratospheric temperatures the amount of water vapor even in saturated air is infinitesimal (fractions of a milligram per cubic meter of air); (2) the water vapor itself at such low temperatures has complex properties which complicate measurements. Water vapor was considered close to saturation in the upper layers of the troposphere. Because of the lack of definite data and in order to make calculations of stratospheric temperatures agree, it was theoretically accepted that there is so much water vapor even in the stratosphere that it is close to saturation. Only in 1945 and 1946 did reliable methods of measuring water vapor in the stratosphere become available. The amount of water vapor in the stratosphere proved to be only one tenth the amount assumed. The water vapor content drops sharply in the transition from troposphere to stratosphere. There is not nearly enough water wapor in the stratosphere to maintain by its absorption the temperatures observed there. This does not mean, however, that the theory of radiation equilibrium as a temperature regulator is incorrect, but that the special role of water vapor must to a certain degree be transferred to ozone.

C. Ozone in the Stratosphere

It has long been observed that the spectrum of the sun and any star at the ultraviolet end is broken at a wave length of about 0.3 micron. Further research revealed that ozone is highly absorbing, starting right at the wave length 0.3 micron. But the amount of ozone in the air close to the earth's surface is

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infinitesimal (0.000001 percent), and therefore absorption of light by atmospheric ozone, it would seem, could not entirely cut off the sun's spectrum around this wave length. However, a much greater amount of ozone might be present in the higher atmospheric layers.

When this idea first arose 25 years ago, no airplane or balloon could ascend higher than 8 to 10 kilometers, and thus the amount of ozone at great heights could not be measured directly. However, development of indirect methods of studying the higher levels began 25 to 30 years ago. These were primarily optical methods, to which later were added acoustic and radio-wave methods. The study of the higher levels by indirect methods is an outstanding accomplishment of present-day geophysics, and a Soviet scientist, Academician V. G. Fesenkov, is a pioneer in this field.

In 1915, Fesenkov published a work in which he showed that the distribution of air density up to heights of 100 to 200 kilometers could be studied by measuring the brightness of the sky at twilight. The twilight method has been widely used in the USSR and abroad in recent years. The method is as follows: We assume that after the sun goes down the rays come from beneath the horizon at an angle a; then the earth's shadow in the zenith is equal to h. A short time later, the angle of submersion of the sun beneath the horizon increases to a_1, and the earth's shadow ascends to h'. During this time, therefore, sunlight has been cut off from the atmospheric layer h' - h, which slightly decreases the brightness of the sky.

Shortly after the development of the twilight method, other optical methods of studying the higher atmospheric layers were devised, e.g., by observations on meteorites and on night-sky luminescence, etc. Then, 15 to 20 years ago, optical methods of measuring the ozone content up to several score kilometers by observations from earth were developed. These measurements showed that most of the ozone is situated in the higher atmospheric layers, the density being at a maximum between 22 and 25 kilometers (Figure 2). In every flight of a stratosphere [illegible], careful measurements have been made to check this important conclusion on the distribution of ozone with height. All direct measurements in the stratosphere, the latest of which was in 1947, have confirmed this result. Experiments with V-2 rockets in the US in 1946 and 1947, in which a spectrograph was raised to 88 kilometers, proved that most of the ozone is situated below 40-50 kilometers.

Ozone left to itself will be entirely converted to O_2 molecules. The permanent ozone content therefore indicates some regular dissociating factor which splits O_2 molecules into oxygen atoms $O + O$. Then ozone molecules can be formed by the collision of O atoms with O_2 molecules.

This dissociating factor is the ultraviolet radiation of the sun with a wave length of 0.18 micron or shorter. Here we encounter the important contemporary "sun-earth" problem. Many are now working on this problem, one of the most important in geophysics and astrophysics.

It was recently proved that ozone has such a strong absorption band in the infrared region around the 10-micron wave length that although the total amount of ozone in the atmosphere is only 0.00002 of the amount of water vapor, the radiation energy absorbed by ozone is only slightly less than that absorbed by water vapor. The difference in vertical distribution of these two gases predetermines their different roles as temperature regulators of the troposphere and stratosphere.

There are many reasons to believe that the concept of ozone as a temperature regulator in the stratosphere will determine the development of the theory of the stratosphere in the future, but this viewpoint needs checking and development. What confirms this viewpoint and what needs critical and careful study?

The point is not solely that there is little water vapor in the stratosphere. Since there is a great deal in the troposphere, almost all terrestrial radiation of those long waves which are absorbed by water vapor remains in the troposphere. On the other hand, terrestrial radiation of that wave length (10 microns) which is absorbed by ozone passes freely through the troposphere.

One can calculate the equilibrium temperature which an arbitrary gas would have if it were the only component of air in the stratosphere. For water vapor it is minus 80 to minus 85 degrees and for ozone it is minus 35 degrees, i.e., 50 degrees higher. Thus, the higher the ratio of ozone to water vapor, the higher the air temperature. Since, in the stratosphere, this ratio increases with height, the temperature also increases. This basic fact could not be explained by theories which did not take the role of ozone into consideration.

Optical measurements have established that the amount of ozone in the stratosphere depends on geographical latitude and time of year. The amount decreases toward the equator and increases toward the poles, and it is maximum in spring and minimum in fall. Noting this fact, one can easily explain by radiation equilibrium the decrease in temperature of the stratosphere and the increase in height of the tropopause from the poles to the equator and the seasonal variations in height of the tropopause. Until recently, there was no theoretical explanation of these basic facts.

The quantitative side of the new theory is still in need of development, mainly because of the lack of necessary data on water vapor and ozone content for various levels. Information on the ozone content is lacking for the most interesting part of the stratosphere, i.e., the layer from 10 to 20 kilometers. Systematic data for individual thin layers cannot be obtained by existing methods, nor can the variation in ozone content be measured in the transition through the tropopause, although this is of extreme importance. Well-known specialists in many countries are working to improve the methods for the determination of ozone content. One new method that promises improvement -- searchlight sounding of the atmosphere -- is now being successfully developed in the Geophysics Institute, Academy of Sciences USSR. In this method, the powerful beam of a searchlight is directed skyward. By observing afar the beam at various points with the help of special instruments, one can study the various phenomena characterizing the individual atmospheric layers. The Geophysics Institute has made considerable progress in this direction, having conducted such optical sounding of the atmosphere up to heights of 55 kilometers. At any rate, the theory of the stratosphere will be advanced considerably after more accurate data is obtained on the vertical distribution of water vapor and ozone around heights of 14 to 18 kilometers.

D. Temperature of the Higher Atmosphere Layer

Soviet rasonde measurements, which have reached 25-30 kilometers, indicate a slight increase in stratosphere temperature with height. In the past decade, however, important results obtained by indirect methods indicate that special temperature conditions prevail in the higher levels. These may briefly be characterized by the rule, "the higher, the hotter." We will first consider acoustic data.

In World War I it was observed that sometimes a heavy artillery barrage could be heard at great distances but with regions of silence. Later, the "anomalous zones of audibility" were established by acoustic measurements in heavy explosions. Normal audibility disappears at a distance of 30-50 kilometers. A region of silence follows, and then still further from the point of explosion the sound is heard again (Figure 3). It has been theoretically proved that the sound waves are refracted from air layers 35 to 60 kilometers high. The sound waves can be refracted back to earth if the air temperature (upon which the velocity of sound waves depends) in the return layers increases with height. The phenomena observed can be explained if we assume that the air temperature increases rapidly with height from 25-30 kilometers to 50 kilometers, e.g., 30 degrees at 40 kilometers, about 60 degrees at 50 kilometers, and 75 degrees at 60 kilometers (Figure 4). /"On the assumption of a uniform increase of temperature with altitude setting in at about 30 kilometers, Whipple calculated the temperatures necessary to account for the transit times of the sound and the angles of the downcoming rays as observed during daylight hours of the months from May to September in the years 1928 - 1930. The temperatures came out around 7 degrees at 40 kilometers and 77 degrees at 55 kilometers. -- Terrestrial Magnetism and Electricity, edited by J. A. Fleming, McGraw-Hill, New York, 1939, reprinted 1949, p 501)

The steady increase in temperature with height in these layers is confirmed by twilight observations. Since the density of air in the levels from 20-30 to 150-250 kilometers can be found by this method, temperature and pressure distributions can also be calculated. This method has been used extensively in Germany, the US, Britain, France, and other countries. Even today, however, Soviet scientists lead in this method because of the theoretical and basic experimental work of the Abastumyan Astrophysical Observatory, Academy of Sciences Georgian SSR, and the Geophysics Institute of the Academy of Sciences USSR. In 1946, the density of air up to heights of 250 kilometers was determined from measurements at the Abastumyan Observatory. From these densities, the air temperatures were calculated; at 200 kilometers, the temperature was calculated to be 600 degrees.

Thus, the opinion, held until recently, that the upper layers of the atmosphere are very cold is now refuted. Interesting results have been obtained by observations on the luminescence of meteors. Simultaneous photography of meteors from two points permits one to determine the height, speed, and brightness of the meteor for various points of its trajectory. The values of air density obtained by this method agree well with those obtained by twilight observations.

For the past 6 to 8 years, a number of determinations of air density have been made with the help of reflected radio waves. All these methods taken together permit one to construct an approximate picture of the temperature of the upper stratosphere. (Figure 5). Above 60 kilometers the temperature begins to drop and reaches a minimum at 80 kilometers. Above 80 kilometers the temperature begins to increase rapidly again, and this increase continues to 200 kilometers. But above 100 kilometers we enter a special region of the atmosphere, the ionosphere.

E. Composition of Air in the Ionosphere and the Problem of Vertical Mixing

The ionosphere is divided into the following layers: the E-region at 100 kilometers and the F-region at 250-300 kilometers; the latter is sometimes subdivided into the F_1- and F_2- regions. There is also the weakly reflecting D-region at 50 to 70 kilometers, which operates only on the longest (kilometer) wave lengths.

The chemical composition of air in the levels above 100 kilometers can be determined by studying the spectrum of the northern lights and the luminescence of the night sky. Photographing the northern lights simultaneously from two points 10 to 50 kilometers apart permits determination of their height. This method showed that the lower edge of the northern lights never drops below 100 kilometers /"An interesting case of an auroral arc with a red lower border was measured at the Auroral Observatory at Tromso in 1932 by Harang and Bauer. They found the arc descended to an altitude of 65 to 70 kilometers. This is the lowest height as yet measured by the photographic method." -- J. A. Fleming, Op. Cit., p 587/. The upper edge extends to 250-400 kilometers and in rare cases to 800-1,000 kilometers. In the laboratory, the chemical composition of a gas can be determined by passing an electrical discharge through the gas and studying the spectrum given off by the gas. The northern lights, in the same way, are just luminescence caused by an electrical discharge in the air. Thus, the air composition up to 100 kilometers can be determined by a study of the spectra of the northern lights.

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Another interesting natural phenomenon, called night-sky luminescence, was discovered some 30 years ago. The brightness of the night sky on a clear moonless night, as shown by measurements and calculations, is two or three times "greater than necessary," i.e., greater than can be explained by the light of all stars. It was proved that the higher atmospheric levels, mainly the level from 130 to 180 kilometers, shine continuously. Study of the spectra of this luminescence, the nature of which is still not completely clear, permits one to determine the composition of the upper levels of the atmosphere over any part of the world, and not just over polar regions, as in the case of the northern lights. Studies showed that the air composition even in the highest levels was the same (nitrogen-oxygen) as that prevailing in the lower levels. This result was unexpected, since it had previously been considered from the fundamental principle of hydrostatics (which yields the well-known "barometric" formula) that light gases must predominate in the higher levels and that therefore the ionosphere must be almost completely hydrogen. Now it has been proved that hydrogen does not exist in the stratosphere and ionosphere, at least not as a permanent and noticeable component. Thus, the atmosphere is "mixed" at all heights. This result is not surprising since, according to the stratosphere theory previously discussed, there is no vertical mixing in it, i.e., the stratosphere is a region of stable vertical equilibrium.

The problem of a "mixed" atmosphere is one of the most important in present-day geophysics. Complex analyses of air samples taken from various levels up almost to 29 kilometers have recently been undertaken in various parts of the world. The studies have been concentrated on the content of oxygen and helium. The oxygen content up to 20 kilometers is strictly constant, i.e., 20.9 percent by volume. There is a slight decrease in the oxygen content above 20 kilometers, reaching 20.4 percent at $28\frac{1}{2}$ kilometers (Figure 6). There is 0.00052 percent helium at the earth's surface, and 0.00054 percent at 25 kilometers. Geophysicists must explain the mechanism of vertical mixing of air in the stratosphere and ionosphere. The temperature criterion of vertical stability of the stratosphere is of course incomplete. Horizontal air movements must be taken into consideration, especially since, as we shall see below, there are permanent high-speed air flows in the stratosphere and ionosphere.

F. The Ionosphere and the Sun

The spectra of the northern lights and the luminescence of the night sky show that oxygen is completely dissociated in the ionosphere. In the past 3 to 5 years, evidence has appeared on the partial dissociation of nitrogen, but this question is still under discussion.

The agent that supports permanent dissociation and ionization of air in the ionosphere is solar radiation. When sunspots increase, ionization of the upper layers is intensified, accompanied by disturbance of radio communication, magnetic storms, and especially bright northern lights. But what is the radiation of the sun that produces ionization and dissociation; is it ultraviolet or corpuscular? Many are working on this very important problem of present-day astrophysics and geophysics. There is evidence for both types of radiation.

Several eclipses have been used for observations with the help of radio waves on ionization variations during optical and corpuscular eclipses. The active effect of ultraviolet radiation upon the F-region (10-20 percent decrease in ionization during optical eclipse) was established beyond question. The influence of a particle (corpuscular) eclipse was not observed. The observations of Ya. L. Al'pert /an article by Al'pert, "The Structure of the Atmosphere and the Processes in the Region of the F-Layer" appeared in Zhurnal Eksperimental'noy i Teoreticheskiy Fiziki, Vol XVIII, No 11, Nov 1948; [redacted] and B. N. Gorozhankin near Moscow during the 9 July 1945 eclipse permitted some conclusions on the influence of solar corpuscular streams with velocities of 400-600 kilometers per second and higher. A number of observations with the newest equipment during future solar eclipses are still necessary to clear up all essential facts on the dissociating and ionizing action of solar radiation on the ionosphere.

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G. Wind in the Stratosphere

The study of air currents in the upper layers of the atmosphere is a problem of great practical and theoretical importance. The development of a theory of general atmospheric circulation, the principles of the general study of movements of the atmosphere and the theoretical basis of weather forecasts, and demands of long-range artillery, rocket aviation, and acoustic reconnaissance all require information on the speed and direction of air movements at various heights and at various points of the globe, dependent on the time of day and season. Geophysics still lacks the required data, and it is urgent that it be obtained.

First in the methods of studying winds in the stratosphere are observations on noctilucent clouds. These clouds are sometimes visible after sunset and before sunrise. It has been established that noctilucent clouds are always located at an almost constant height, i.e., 80-83 kilometers. This constancy of height is apparently connected with the presence of a permanent powerful temperature inversion which begins right at this level. These clouds move rapidly, and their speed can be measured by photography. Second are meteor trains, which permit determination of the speed and direction of wind at various heights. Some information on the movement of "clouds" of high ion concentration in the ionosphere has recently been obtained by radio observations.

Important information on this problem may also be obtained by acoustic measurements of the zones of anomalous audibility in powerful explosions. This method has not received the development which it deserves. Soviet geophysicists (Prof S. V. Chibisov and others) are credited with the best theory on this complex phenomenon.

Finally, in 1946, an Englishman made a number of observations on the drift of smoke formations from special smoke chambers fired from a zenith cannon up to heights of 30 kilometers. The presence of powerful and regular air currents at various atmospheric levels was established. A typical representation, in which some data is collated, is shown in Figure 7.

Wind velocity in the troposphere increases with height, reaching a maximum of 20 to 25 meters per second beneath the tropopause. At this height, moreover, the winds have a prevailing direction. In the stratosphere, the wind velocity begins to decrease rapidly with height, reaching a minimum of 6 to 8 meters per second at 19 to 22 kilometers. In the higher layers, however, an exceedingly rapid intensification of winds is observed. The wind velocity approaches 70 meters per second at 40 kilometers, and 140 meters per second at 60 kilometers. The powerful temperature inversion beginning at 80 kilometers may possibly play the role of a "second tropopause" in certain respects. In any case, the wind velocity apparently reaches its maximum (up to 160 meters per second) here and decreases in the higher levels.

The prevailing wind direction in the "second tropopause" is directly opposite to the wind direction in the tropopause proper. It is possible that these two tropopauses constitute an important element of a closed circulation system in the stratosphere, and that the much greater velocities in the upper tropopause are necessary according to mass balance or conservation of mass (since the air density decreases with height).

/Appended figures follow./

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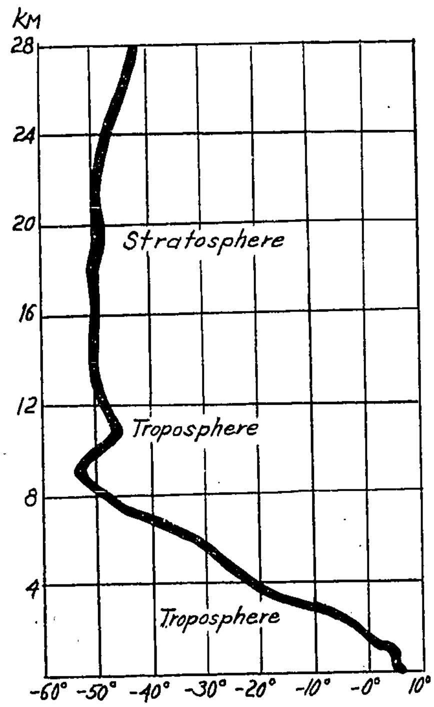

Figure 1

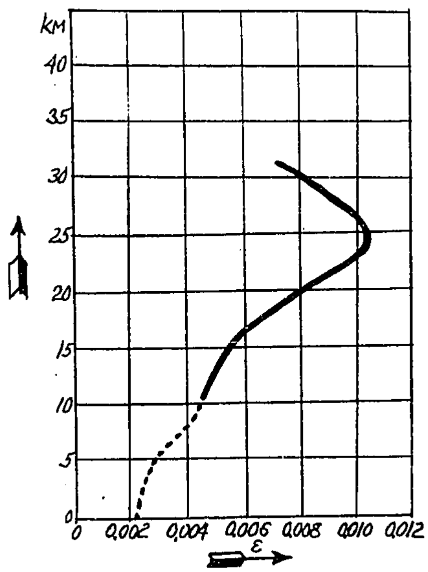

Figure 2

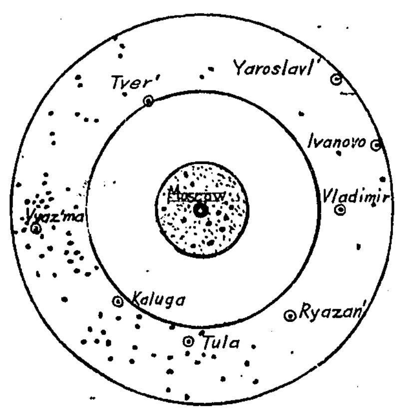

Figure 3

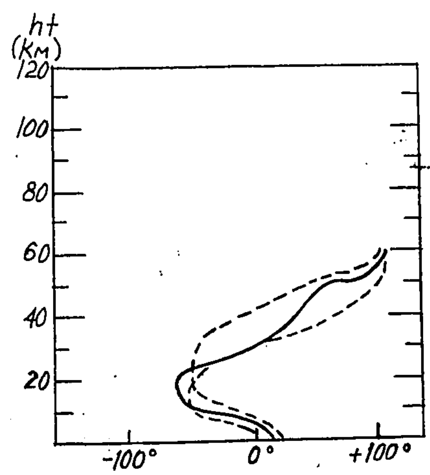

Figure 4

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