ART. XLVI.—*Note on Atmospheric Radiation*; by FRANK W. VERY.

THE heat which gives to any layer of the atmosphere its observed temperature is derived from several sources which may be designated as follows:

- + h_c = heat transferred by convection from warmer and lower layers of air.
- + h_p = heat transferred by molecular penetration from warmer neighboring air masses in any direction.
- + h_w = heat derived from the condensation of aqueous vapor.
- + h_s = heat from absorption of solar radiation by the molecules of gases and vapors, or by floating dust from which it is transferred to gaseous molecules.
- + h_t = heat from a similar absorption of terrestrial radiation.
- + h_a = heat produced by absorption of radiation from warmer air masses, situated either above or below, but usually below. Here each atmospheric ingredient absorbs selectively and solely the radiations of those special wavelengths which it can itself emit.
- ± h_i = heat from chemical changes, such as ionization by solar ultra-violet radiation. The heat produced in this way may be included under the heat (h_s) from absorption of the sun's rays. The direct effect of ionization on temperature is probably small, but it may have important secondary consequences through the production of peculiar substances in small amount, but possessing extraordinary powers of selective radiant absorption and emission.
- ± h_q = heat imported, or abstracted by the planetary atmospheric circulation.

The relative importance of these sources of thermal supply varies greatly at different elevations. In the isothermal layer (3), the heat received is

$$H_3 = h_s + h_a + h_p \pm h_q.$$

Convection may not have ceased entirely, but it is very small, and has been omitted from the expression. There are no clouds here and terrestrial radiation passes through unchanged, having suffered all the absorption of which it is capable in lower layers. The heat from absorption of solar rays becomes exceptionally powerful where the solar radiation first enters the aqueous atmosphere in the higher levels of the isothermal layer.

Between the isothermal layer and the air near the ground lies the great body of the cloud-producing atmosphere (2), where

$$H_2 = h_c + h_p + h_w + h_s + h_a + h_t \pm h_q.$$

Near the earth's surface, the absorption of terrestrial radiation replaces that of the sun's rays to a great extent, because the absorbable part of the latter has already been removed by the upper air, except as the dust of the lower air absorbs radiation of every wave-length. The terrestrial radiation is chiefly effective in warming a shallow layer of air (1) near the ground, and its absorbable rays are soon sifted out in passing through the lower humid layers; but it is also efficient at any level where there is cloud and where the regions of absorption in the spectrum of terrestrial radiation are much broader. Emphasizing this importance of heat from absorption of terrestrial radiation by aqueous vapor, it is placed first on the list in the enumeration of heat sources for the superficial layers.

$$H_1 = h_t + h_c + h_p + h_w + h_a + h_s \pm h_q.$$

The heat thus acquired may be removed by evaporation of precipitated water particles ($-h_e$), by atmospheric radiation ($-h_r$), by convection ($-h_{c'}$) and by penetration ($-h_p$). If there is thermal equilibrium,

$$\begin{array}{ll} \text{at level} & (3), \quad h_s + h_a + h_p \pm h_q - (h_r + h_{p'}) = 0, \\ \text{" " } & (2), \quad H_2 - (h_e + h_r + h_{c'} + h_{p'}) = 0, \\ \text{" " } & (1), \quad H_1 - (h_e + h_r + h_{c'} + h_{p'}) = 0. \end{array}$$

Except in the upper air, the distance through which atmospheric radiation can proceed before it is reabsorbed by the air, is so small that convection and penetration might be expected to supersede radiation as available modes of thermal transference from one body of air to another. We are at last able to apply a critical test to this supposition.

The study of the vertical distribution of thermal losses in the earth's atmosphere which Professor Bigelow has made,* permits for the first time a comparison of atmospheric radiation, transferred from layer to layer in the free air, with that computed from laboratory measures.

The radiation from a layer of pure dry air, 1 meter in depth, and having an excess of temperature of 10°C. , may be taken as equivalent to a transference of 0.00006 gram-water-degree-Centigrade units of heat per second through each square centimeter of surface.† Bigelow divides the atmosphere into layers 1000 m. deep. The difference of temperature at the top and bottom of each layer is somewhat less than 10° , varying in fact between 5° and 7°C. throughout a considerable part of the first 10,000 meters. If radiation (R) from layer to layer is

* Frank H. Bigelow—"The Thermodynamics of the Earth's Non-adiabatic Atmosphere," this Journal, xxxiv, 515-532.

† Frank W. Very—"Atmospheric Radiation." Bulletin G, U. S. Weather Bureau, p. 112, 1900.

simply proportional to the depth of the layers and to the fourth power of the absolute temperature, we get the values in the third column of the following table. This, however, in no case represents the *direct* radiation of the atmosphere from layer to layer, because the selective radiations of the gaseous molecules can proceed but a little way before they are absorbed by other molecules of the same gas. These in turn radiate again to cooler ones at a still higher level, and so on,* but the number of successive transferences of heat is very great even in a layer no more than one thousand meters thick, and the process is a slow one, not to be compared for rapidity with the rate of escape of unimpeded radiation.

Taking averages through the first 15,000 meters of air, we get the following mean values of energy expended as radiation in large calories per square meter, for comparison with Bigelow's ΔQ , or "heat expended."

Elevation	Per thousand meters		
	ΔT	R (computed)	ΔQ (observed)
Upper layer 15000—10000 ^m	0.96 C.	0.057	0.408
Middle layer 10000—5000	7.3	0.429	0.237
Lower layer 5000—0	5.4	0.314	0.090

The sudden diminution of the computed radiation (from stratum to stratum) in the upper layer follows from the entrance into the isothermal region, and from the diminution of ΔT ; but this does not imply a cessation of atmospheric radiation in this nonadiabatic layer. On the contrary, the observed increase of ΔQ in the upper layer is presumably due very largely to direct radiation to outer space. That this outgoing radiation produces no appreciable fall of temperature with increasing elevation, appears to be because the heat of the upper layer is continually replenished by absorption of the radiation from the lower air, but especially because the solar rays are undergoing their initial absorption, and though some of the absorbent material, such as aqueous vapor, is excessively rarefied, there are certain rays which are so powerfully absorbed that they suffer loss in passing through the most tenuous layer.†

The values of R, computed on the above assumption, are considerably greater than those of ΔQ in the lower atmosphere,

* *Op. cit.*, pp. 114-115. † F. W. Very—*Atmospheric Radiation*, p. 123.

where we must presume either that atmospheric radiation is itself impeded by vaporous absorption, or that convection plays a larger part in the denser air. The actual mean direct radiation between neighboring air masses, which lies at the foundation of the successive absorption and radiation of the indirect process, must be smaller than that assumed. The extension of an observed air radiation for a layer 1 meter thick, at an excess of 10° , to a layer 1000^m thick with the same excess, or a proportional one, is only justifiable on the supposition that in the passage of heat from molecule to molecule by radiation, the small distances traversed in successive steps compensate for the small differences of temperature and feeble radiations of the separate interchanges whose integral finally reaches a sum total of energy equivalent to that of a direct transmission. Whatever doubt one might have as to the legitimacy of the assumption that the two processes are even moderately equivalent, is now set at rest by the near agreement of the exponent of T for the indirect process with the exponent (4) required by Stefan's law. This seems to prove that, after all, the process is a radiative one, rather than convective.

The potential radiation function which Bigelow derives from the internal energy of the air by the formula

$$K = \frac{U_1 - U_0}{v_1 - v_0},$$

where U_1 and U_0 are the internal energies at the top and bottom of a layer, and $v_1 - v_0$ is the change of volume of unit mass of air in the same interval, at an altitude of 18,000 meters, is about 0.16 of that at the earth's surface, which is 0.4 of that for a black body.* This ratio is not improbable considering the variation of the composition of the air in a vertical column; but a distinction must be preserved between the passage of

* With Kurlbaum's constant of radiation, $R = 5.32 \times (10)^{-4} \times T^4$ joules/sq. m. sec., a black body radiates at 289° and 225° abs. C. (which are temperatures observed in Europe at 0 and 18,000 meters) 3,711,000 and 1,363,000 mechanical K.M.S. units, or 0.532 and 0.196 small calories per sq. cm. per min. (Ratio = 2.71 : 1). Bigelow obtains a ratio of potential air radiation = 6.37 : 1. The sum of the values of the radiant potential (K) between the surface and 18,000 meters altitude is about one-third of the difference for black radiators at the given temperatures, which may mean that the emission bands of the air spectrum cover about one-third of the entire range. On rising in the air some of the vapor bands become narrower and drop out, and thus the potential radiant function diminishes more rapidly than that of the black body for the same fall of temperature. The air radiation from laboratory measurements agrees with the average ΔQ , which therefore represents the actual air radiation to space and increases upwards with the progressive removal of the outer obstructing layers. The surface layers of air have large K and small ΔQ of necessity, for it is only because these layers are not free to radiate to space in accordance with their high potential that the lower air can maintain its relatively high temperature.

energy through the atmosphere by the modified radiant process, outlined here, and a pure radiation. The sudden increase in the constant second differential of Q at the isothermal level, strongly suggests an accession of immediate radiation to space above this point, and a progressive diminution of the indirect radiant process from thence outward, together with a cessation of aqueous condensation which supplies considerable heat to the lower layers, while further loss of temperature is only permitted through the gradual removal of absorbent substances which prevent the passage of radiation of great wavelength, characteristic of still lower temperatures.

The methods employed by Bigelow still retain something of empiricism. Wherever a temperature gradient less than that of the adiabatic rate prevails in the atmosphere, some heat must have been supplied by radiation, or by condensation of aqueous vapor, or in other ways; and this extraneous addition is not taken into account by the formula which connects the density with temperature and pressure. It is known from laboratory experiments that the specific heat of air at constant pressure is very nearly constant between -39°C. and $+200^{\circ}\text{C.}$ Wherever the values of C_p computed by Bigelow's formula depart from the true value given by laboratory experiment, the deviation of the fictitious or apparent C_p denotes that only a part of the thermal variation with the altitude is due to simple mechanical transportation and expansion of masses of air. The deviation becomes progressively greater in the upper air where production of heat by absorption of solar radiation is large. From the intimate relation between C_p and R , the gas factor, a corresponding variation is produced in the fictitious value of R . Similarly, if the computed value of the air radiation is larger than that of ΔQ in the lower layers of air, this must mean that the data employed include other phenomena besides those of radiation. Although the upper air is more transmissive than the lower air for radiations of wave length less than 15μ , the final limit to further decrease of temperature by atmospheric radiation to free space appears to result from the virtual opacity of the air to longer waves than these, coupled with the fact that a temperature has been reached at which these long-waved radiations constitute the greater part of the radiant output. This limit is only extended by the very gradual removal of the last traces of absorbent at still greater altitudes. These remarks are not intended as a criticism of the methods, for it is difficult to see how any others can be used, but are made to point out the limitations of an analysis which is obliged to deal with data covering a variety of simultaneous processes in unknown proportions, and in the endeavor to elucidate the meaning of the results.

Although the radiation function in the lower air, where only indirect radiation exists, can be fairly well represented by a radiation formula with the exponent of T (the absolute temperature) equal to 4, so that indirect radiation is still satisfied by Stefan's law with small changes in the constant,* yet in the upper isothermal layer where free radiation ought, if anywhere, to be in control, the exponent of the radiation formula suddenly becomes negative. This discrepancy, however, is more apparent than real, and appears to be due to the superposition of several effects attributable to the progressive removal of absorbent vapor in the upward direction, combined with a special absorption of solar rays and the limitation of long-waved radiation.

The observed value of air radiation has an immediate application to the phenomena of the nocturnal deposition of dew where the atmospheric cooling concerns an air layer only a few meters thick; but this value may require modification when applied to the conditions of the elevated isothermal region. Here the diminished radiant mass in unit volume has the outflow of its radiation of smaller wave-length than 15μ proportionally less obstructed through absorption by its own substance, which tends to give constant radiation in spite of varying density, and thus there is a new freedom of radiation from the upper surface which was not possessed by the air at lower levels, while at the same time there is a strong accession of thermal energy from absorption of the sun's rays by the first portions of aqueous vapor encountered. This absorbent layer immediately becomes a radiant one and its extra heat is dissipated by radiation to outer space. (The region of the accession of freer atmospheric radiation to outer space is about 3000 meters higher in the torrid zone than in temperate latitudes and all of the data are correspondingly modified.) This seems to be the meaning of the sudden increase in the loss of heat on entering the isothermal layer, which passes, according to Bigelow's computation, from -140 in mechanical K.M.S. units per 1000 meters for the lower layers, to -362 per 1000 meters for the isothermal layer.

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* We knew already that, within the very limited range of its selective radiation, the maximum radiant layer of a gas behaves like a black body.