ABSORPTION OF RADIATION BY WATER VAPOR AS DETERMINED BY HETTNER AND BY WEBER AND RANDALL

By H. WEXLER

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In a recent paper, the author[1] presented meteorological evidence showing that the combination of Hettner's coefficients of water vapor absorption[2] with an abnormal amount of atmospheric carbon dioxide, as assumed by Brunt[3] and referred to by the writer as model A, leads to values for atmospheric absorption of long-wave radiation that are too large, whereas Weber and Randall's absorption coefficients[4] applied to an atmosphere of normal carbon dioxide content (model B) are in good agreement with observations. It was also pointed out (p. 129) that the disagreement of the former with observations persists even if the normal atmospheric carbon dioxide content is used, which indicates that Hettner's absorption coefficients are too high. In this note, additional evidence, both laboratory and meteorological, is presented, showing that model B, but not model A, accounts for absorption as actually observed in the atmosphere, except under conditions of low pressure and temperature.

First, however, an error in figure 2b of the author's former paper must be pointed out: Weber and Randall did not state the room temperature at which their measurements were made; and, acting on the best information that could then be obtained, the writer assumed it to have been 22.5°. Later it was found that Ramanathan and Ramdas[5] had assumed it to have been 26.3° (not 30° as stated in the former paper), which has since been verified as the correct value. Hence the coefficients in figure 2b should be decreased by about 20 percent; figure 2a will remain unchanged. This correction has no effect on the writer's former conclusions; 1 mm of precipitable water vapor still transmits less than 10 percent in the band from 17μ to 25μ.

Recently Falckenberg[6] has measured the total absorption of long-wave radiation by water vapor; and his results show much less absorption than Hettner's coefficients would indicate, although his demonstration is not so convincing as it might be, because he had to make a sixfold extrapolation of one of his curves.

In a discussion of the Polar Year observations at Mount Nordenskiöld, Spitsbergen (1,049 meters), Olsson[7] found that the average net loss of radiation during clear weather in the winter half of the year was 0.147 gm cal/cm²/min. at a temperature of −20.7° C.[8] Practically all the observations were made at a temperature of about −20°; the station was generally above the ground inversion and in a region of strong cyclonic activity, and hence probably almost continuously exposed to polar maritime air. The curves in figure 4 of the author's paper[1] provide a means of checking Olsson's result: Assuming the snow surface at Mount Nordenskiöld to radiate as a black body at a mean temperature of −20.7° C., it would radiate 0.335 gm cal/cm²/min. From the curves in figure 4 it is possible to find the radiation from the atmosphere. To find the radiation coming from a saturated atmosphere of abnormal carbon dioxide content which absorbs radiation according to model A, it is necessary to find the mean temperature of the surface layer of air that contains 0.15 mm of precipitable H_2O. With a surface temperature of −20° and a lapse rate of 0.9°/100 m (approximately the saturated adiabatic value at −20° and 900 mb), the thickness of such a layer is about 150 meters, and its mean temperature is about −21.4°. Using this temperature in curve (*b*), figure 4, the atmospheric radiation is found to be 0.248 gm cal/cm²/min. Hence the net loss of radiation is 0.335−0.248=0.087 gm cal/cm²/min., which is in poor agreement with Olsson's value. To find the radiation coming from a saturated atmosphere of normal carbon dioxide content which absorbs radiation according to model B, it is necessary to find the mean temperature of the surface layer of air which contains 1 mm of precipitable H_2O. Under the same conditions as above, the thickness of such a layer is about 1,000 meters, and its mean temperature about −25.2°. From curve (*c*), figure 4, the atmospheric radiation is found to be 0.193 gm cal/cm²/min. and the net loss of radiation is 0.335−0.193=0.142 gm cal/cm²/min., which agrees closely with Olsson's value of 0.147 gm cal/cm²/min.

During the past winter, daily simultaneous outgoing radiation measurements and airplane soundings were made at Fairbanks, Alaska (65°51′ N, 147°52′ W.), as part of an investigation of the formation and structure of polar continental air that is being conducted under a grant from special research funds provided by the Bankhead-Jones Act. It is hoped to publish these data in detail later; but it may be mentioned here that when the values of radiation coming from the cloudless atmosphere were plotted against temperature of the isothermal layer (as determined by the airplane sounding) all but a few of the 48 points fell between curves (*b*) and (*c*) in figure 4 of the previous paper. At temperatures near 0° C., most of the points were closer to curve (*b*) (determined from model A); at intermediate temperatures they were located about midway between the two curves; and at temperatures from about −20° C. to about −30° C., they were grouped about curve (*c*) (determined from model B). The radiation observations were made with the Abbot-Aldrich Melikeron; and some of the values of atmospheric radiation derived from them are undoubtedly too large, since 2/10 clouds and also local smoke and light fog were included in the clear sky category.

The writer has presented three separate examples in which model B gave the better agreement with meteorological observations[1]. The first of these is the magnitude of ground inversions; and a particularly striking instance, shown in the accompanying figure, was observed in a recent airplane sounding at Fairbanks, Alaska, made during nearly calm, cloudless, and sunless conditions. The temperature at the snow surface was −44.3° C., and it increased nearly 20° in the first 35 meters, a layer occupied by a dense ground fog. From 540 meters to about 1,900 meters the temperature was very nearly constant at −15° C., and thereafter decreased in a normal manner to −35° at 5 km. From the temperature of the

[1] H. Wexler, Cooling in the Lower Atmosphere and the Structure of Polar Continental Air, MONTHLY WEATHER REVIEW, 64, 122, April 1936.
[2] G. Hettner, Über das ultrarote Absorptionsspektrum des Wasserdampfes, Ann. d. Phys., 55, 476, 1918.
[3] D. Brunt, Phys. and Dyn. Meteorology, Cambridge, 1934.
[4] L. R. Weber and H. M. Randall, Absorption Spectrum of Water Vapor beyond 10μ, Phys. Rev., 40, 835, 1932.
[5] K. R. Ramanathan and L. A. Ramdas, Derivation of Ångströms' Formula for Atmospheric Radiation, etc. Proc. Ind. Acad. Sci. 1, 822, 1935.
[6] G. Falckenberg, Experimentelle zur Absorption dünner Luftschichten für infrarote Strahlung, Meteorol. Z, 53, 172, May 1936.
[7] H. Olsson, Sunshine and Radiation, Mount Nordenskiöld, Spitsbergen, Geog. Ann., heft 1, p. 93, 1936.
[8] The mean deviation, as found by the author from Olsson's observations is ±0.009 gm cal/cm²/min.

isothermal layer, −15° C., it is possible with the aid of the curves in figure 4 of the previous paper to determine the equilibrium surface temperature. With model A, this temperature is found to be −33.8° C., much higher than that observed; while with model B, it is −45.2° C., only 0.9° lower than that observed. If the latter correctly portrays the radiation properties of the atmosphere, then the calculated difference between the equilibrium temperatures of surface and isothermal layers

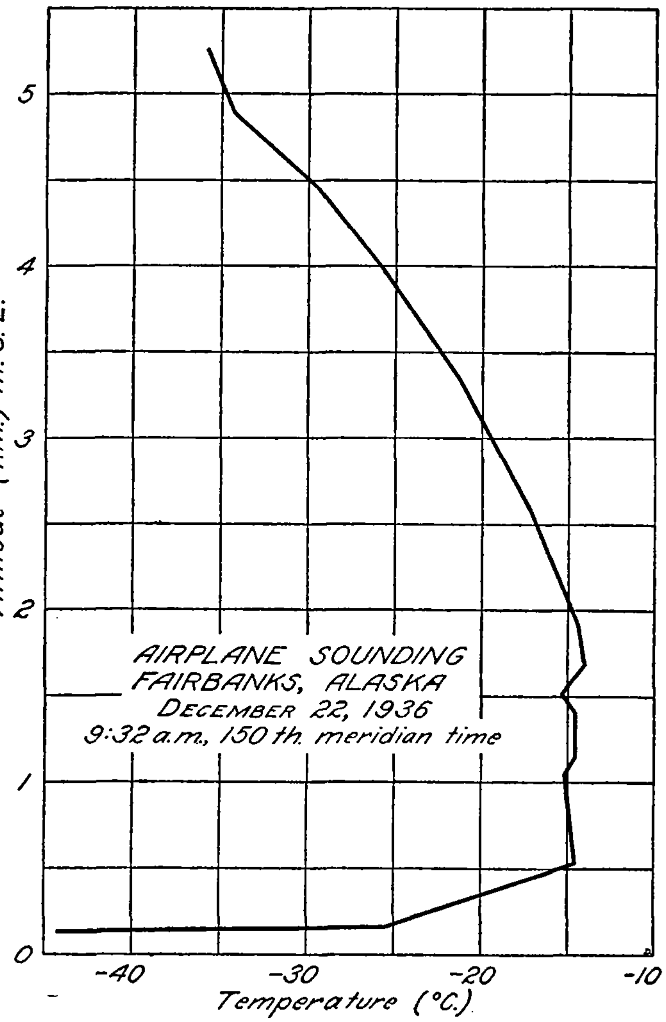

Figure 1.

should not be exceeded by the observed value. The sounding in figure 1 comes closer to satisfying conditions for radiative equilibrium than any heretofore noted by the author. Another sounding made a few hours later at sunset showed an almost identical temperature-height curve.

Two outgoing radiation measurements were made at the time of the soundings and both showed a net loss of 0.020 gm cal/cm^2/min.—a very small amount, as should be expected during the quasi-equilibrium stage that had been attained. However, it seems likely that this value is too small, because the measurements were made in a dense fog and had to be abandoned shortly thereafter on account of frosting of the instrument. According to the curves mentioned above, the net loss of energy at the quasi-equilibrium stage should have been 0.080 gm cal/cm^2/min.

The atmosphere not only loses energy to space by way of the snow surface, but also directly to space by means of the Albrecht emission layer,[9] a layer about 3 km thick situated in the upper atmosphere below the −50° C. isotherm. Albrecht found from Hettner's absorption data that the rate of loss of energy would be nearly equal to that of selective radiation from water vapor and carbon dioxide at −50° C., or about 0.170 gm cal/cm^2/min. If now we examine a calm, clear, sunless atmosphere, with surface temperature 0° C. and a steep lapse rate, such as would be the case in fresh polar maritime air, then the rate of loss of energy to space from a snow surface over which the air is passing can be found by subtracting curve (b) from (a) in the figure 4 previously referred to. At 0° C. the result is about 0.127 gm cal/cm^2/min., much smaller than the loss at the emission layer which Albrecht says is about 0.170 gm cal/cm^2/min. If it is true that less energy is lost directly to space from the surface than from the upper atmosphere, it would be impossible for an atmosphere with an initially steep lapse rate to cool more rapidly in lower than in higher levels. In other words, it would not be possible to transform polar maritime air into polar continental air, that is, into air characterized by a large ground inversion and a very stable lapse rate to heights of 2 or 3 kilometers, as is commonly observed in polar regions during winter.

If, however, we make use of the radiative properties that follow from model B, it becomes possible to account for surface inversions. Curve (c), figure 4, shows the selective radiation from water vapor and carbon dioxide at −50° C. to be 0.135 gm cal/cm^2/min., which is the loss from the emission layer. The net loss from the snow surface at temperature 0° C. is larger, 0.186 gm cal/cm^2/min., and in this case it is possible for the atmosphere to cool from below. However, when the surface has cooled to about −20° C. then its loss of energy to space becomes equal to the loss from the emission layer. If the surface temperature falls below −33° C., then the air above the inversion can also be cooled by radiation, but at a smaller rate than aloft at the emission layer; and as cooling continued, a steep lapse rate would be maintained above a surface inversion, a conclusion which is not in agreement with observations of the structure of polar continental air, which even at very low surface temperatures has a stable lapse rate to some height above the surface inversion. Hence, even on the basis of Weber and Randall's data, the value of the loss from the emission layer is much too high, probably because the effect of low pressure and temperature on the water vapor absorption spectrum is to diminish the continuous character of the spectrum by decreasing the width of the absorption lines and increasing their intensity, as pointed out by Albrecht.[10] That is, the transparent portions of the spectrum increase at the expense of the opaque portions; and at low pressure and temperature, the atmosphere becomes more transparent to radiation. Apparently, the emission layer may no longer be considered as composed only of 2 or 3 kilometers of air below the −50° C. isotherm, but in reality consists of the major portion of the troposphere below this isotherm, with the region of maximum loss of radiation probably situated near the central portion of the layer.

The width of an absorption line is proportional to barometric pressure and to the square root of absolute temperature[10]; hence, at sea-level pressure the effect of low tempera-

[9] F. Albrecht, Der Wärmeumsatz durch die Wärmestrahlung des Wasserdampfes in der Atmosphäre. Zeitsch. f. Geophy., 6, 420, 1930. Über die "Glashauswirkung" der Erdatmosphäre und das Zustandekommen der Troposphäre. Meteorol. Z., 48, 57, 1931.

[10] F. Albrecht, Das Quantentheoretisch gegebene Wasserdampfspektrum über den Wärmeumsatz strahlender Luftschichten, Meteorol. Z, 48, 476, 1931.

ture on the absorption spectrum will not be so great as at the lower pressure of the emission layer. We may assume curve (c) of figure 4 to represent with sufficient accuracy the radiation coming to the surface from a cold atmosphere, but not the radiation leaving the atmosphere at high levels. From observations of polar continental air at low temperatures, it becomes possible to place an upper limit on the amount of radiation that leaves the atmosphere by way of the emission layer. A surface temperature of −60° C., which has commonly been observed in Alaska and Siberia, corresponds to an equilibrium temperature of −34° C. for the isothermal layer above it.[11] From the difference between curves (a) and (c) of figure 4, the net loss of radiation to space from the surface is found to be 0.054 gm cal/cm^2/min. The loss to space from the emission layer must not exceed this amount, for otherwise the atmosphere could not cool and at the same time preserve a stable lapse rate in lower levels. An even lower limit can be placed on the radiation if we notice that the isothermal layer in sounding (a), figure 1, of the writer's previous paper, has a temperature of −41° C., corresponding to an equilibrium surface temperature of −66° C. In this case the net loss of radiation from the surface is 0.044 gm cal/cm^2/min., which is an upper limit to the loss of radiation from the emission layer.

In conclusion, it therefore appears that model B is more satisfactory for computations which involve atmospheric radiation than is model A. Furthermore, the measurements of Weber and Randall, and the effects of low temperature and pressure on absorption, together indicate that the atmosphere is more transparent to long-wave radiation than formerly thought; and this is verified by our knowledge about the structure and rate of cooling of polar continental air. However, further laboratory measurements or theoretical determinations of the absorption constants of long wave radiation by water vapor and carbon dioxide at low temperatures and pressures are much needed.

AIRCRAFT ICING ZONES ON THE OAKLAND-CHEYENNE AIRWAY

By JOHN A. RILEY

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The formation of ice on aircraft is one of the greatest hazards to air traffic today, with the accompanying complications of turbulence which makes the airplane difficult to control and of static which interferes with the operation of vocal and directional radio facilities. The meteorological aspect of the problem has been somewhat simplified in recent years by the recognition that most icing, (as well as other unfavorable conditions, such as precipitation, low ceiling, and poor visibility) occurs in restricted areas: First, along the moving fronts that separate different air masses; and second along high mountain ranges. The worst conditions in the far West occur when the two coincide, that is, while a front is passing over a mountain range.

The icing zones along mountain ranges will be considered first. During the winter, strong westerly winds blowing across mountain ranges cause severe turbulence along the crest of the mountains where the air flow is greatly accelerated. Along the Oakland to Cheyenne route there are four ranges over 8,000 feet high: Sierra Nevada, Ruby, Wasatch, and Rocky Mountains. During cloudy, rainy weather over the coastal region and Pacific slope, snows in the intermountain region, and westerly gales with near freezing temperatures along the mountain crests, a zone of severe icing occurs in the region of turbulence along the top of these high ranges.

Before it was known that severe icing is to be expected in the turbulent region along a mountain crest, the pilot would frequently push into it and, upon starting to take on ice, would turn back and climb higher, repeating the process if necessary until he was above it or returning to the point of departure. Due to a better understanding of the condition, such procedure is no longer necessary; instead the pilot climbs above the icing zone before reaching the mountains, generally 12,000 feet or slightly higher, and maintains this altitude until safely beyond the icing zone on the other side. (See figure 1.)

While he is climbing through clouds, and possibly through light precipitation over the valleys, a slight amount of ice forms as the airplane climbs through a stratum having temperatures ranging from freezing to 25° F. or lower, but in the absence of turbulence the deposit is not likely to be serious; after reaching smooth air at higher altitudes with a temperature of 18° to 20° F., the density of clouds in the West is so reduced that flight can be continued without the formation of a dangerous amount of ice. Pilots report that stratified clouds at high levels are sometimes so tenuous that the outline of convective type clouds penetrating them can be seen; icing and static begin immediately if the convectional cloud formation is entered.

Icing zones have been observed along all the high ranges of the West; they occur whenever strong winds carry clouds and precipitation across them in winter. The Sierra Nevada Range is an outstanding example because of its length and height and because the air flowing over it is characterized by high temperature and humidity. Experimental trips have shown the presence of heavy ice in the updraft along the western slope of the high coastal ranges in southern California. *Severe* icing over the mountains of northern California and southern Oregon is generally associated with fronts rather than the updrafts caused by the mountains, since the route is shielded somewhat from such updrafts by higher mountains west of the airway.

Pilots on the Salt Lake-Cheyenne division have found an icing zone over the Wasatch Mountains similar to that over the Sierra Nevada. A pilot reports that "A cloud bank will build up on the western slope of the range causing over-the-top or instrument flying into Salt Lake City from the east, with broken clouds west of the lake and east of Coalville or Knight. Often the area is more extensive, as the clouds bank up on the Uintas to the south of Knight, necessitating an instrument flight of 30 to 50 minutes" (fig. 2). Another states: "I know of no cases of severe icing being found over the Wasatch while flying above 12,000 feet and with temperatures below 20° F. I have also noted that almost without exception the amount of icing and the turbulence increases several fold during the few minutes we are directly above the highest peaks."

Another pilot, however, has reported rapid accumulation of ice while flying in a cloud at 14,000 feet over the Wasatch Mountains with temperature between zero and

[11] H. Wexler, Cooling in the Lower Atmosphere and the Structure of Polar Continental Air, Monthly Weather Review, 64, 122, April 1936.