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When and why air can be cooler than ground just below: A theory for the Ramdas effect *

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Abstract

This paper offers a brief summary of new theoretical resolution of a sixty-year old paradox, concerning the observation, on calm clear nights, of a minimum in air temperature within less than a metre of the ground. The background to the problem is presented, and the physical basis of the new theory described. It is shown that two factors ignored in all previous discussions of the problem, namely, surface emissivity and thermal conductivity of the soil, play crucial roles in determining when a lifted minimum occurs.

Key words: Micrometeorology, lifted temperature minimum, Ramdas effect, atmospheric radiation, frost, Rayleigh-Benard instability.

In 1932, Ramdas and Atmanathan published a two-page paper[1] (which I reproduce in entirety as Fig. 1, as the paper appeared in a German journal that is not easily accessible) reporting that on calm clear nights air just above the ground (at heights of up to about a metre) can be cooler than the ground by a few degrees. This report, of what we shall call the lifted temperature minimum or the 'Ramdas effect', was for several reasons received with much scepticism. First of all, conventional wisdom has been that during night, the temperature is lowest at (and not above) the ground (and incidentally highest, again at the ground, during day); this wisdom has apparent support from standard observations of air temperature, such as those reproduced in Fig. 2, adapted from a well-known text on micrometeorology[2]. In actual fact, these observations stop at the standard screen height of 1·2m, and so are not necessarily inconsistent with a lifted minimum below that height. A more serious objection is that such a cold air layer above the ground, resulting in heavier air on top, should be subject to the classical Rayleigh-Benard instability. A calculation of the Rayleigh number, based on the temperature differential over

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THE VERTICAL DISTRIBUTION OF AIR TEMPERATURE NEAR THE GROUND DURING NIGHT.

By

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(With 1 fig.)

It is usually considered that nocturnal temperature inversions near the ground are due to the more rapid cooling of the ground by radiation during the night than the adjacent air and that the consequent lowering of temperature of the air near the ground is due to conduction. This is no doubt true for temperate latitudes where the intensity of solar insolation is decidedly smaller than in the tropics, and, in winter, the duration of sunshine is also less. But in India, recent measurements show that even at the epoch of minimum temperature in the cold season, the ground is at a higher temperature than the air immediately above, and that the inversion layer begins, not at the surface as is commonly assumed, but at some height above it.

Observations of air temperature were taken with an ASSMANN Psychrometer at different heights over dry ground at places so far apart as Poona (Lat. 18° 31′ N., Long. 73° 55′ E.), Agra (Lat. 27° 10′ N., Long. 78° 5′ E.), Madras (Lat. 13° 4′ N., Long. 80° 15′ E.) and Bhadrachalam (Lat. 17° N., Long. 81° E.) during the cold season of 1931 to 1932. The temperature of the surface of the ground was also measured with an ordinary Thermometer while these observations were being taken. Curve I of the figure shows a typical example of the vertical distribution of temperature at Poona on the 29th November, 1931, about 45 minutes before sunrise. It will be seen that the temperature very rapidly falls from 18.1° C., at the surface to 12.3° C. at 25 cm. above it and then gradually up to 150 cm. The usual inversion begins at this level. Curve II represents one of a series of observations taken at Agra by Mr. S. P. VENKATESWARAN at the request of one of us. Here it will be seen that (a) the difference between the temperature of the surface and that of the air immediately above it is much smaller and (b) the inversion starts at a much lower level. At Bhadrachalam where the observations were taken above loose sandy soil before sunrise during several mornings, a fall of temperature up to 20 or 30 cms. with a rising

tendency later was noticed. Observations taken at Madras in January 1932 also show similar results.

From the accompanying figures it will be seen that in the tropics, the ground heating is so strong during day-time that the surface temperature is always higher than the temperature of the air above. There is, however, no doubt that the ground loses heat at a faster rate, since the difference between the surface temperature and that of the air immediately above, is consistently less at the epoch of minimum temperature than during the early hours of the night; but the cooling of the surface is not so rapid as to bring about a lower temperature than in the air above.

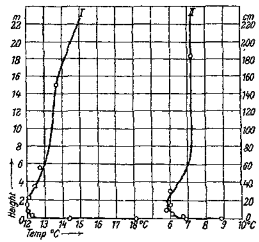

Fig. 1.

I Poona, Nov. 29, 1931, 0600 hrs D. S. T.
II Agra, Nov. 29, 1931, 0536 hrs D. S. T.

It will be noticed that the level at which the inversion begins is higher at Poona than at the other places mentioned above. The Observatory lies in a comparatively low land and the drainage of air down the neighbouring slopes is likely to cause an accumulation of the cold air near the Observatory and thereby cause the inversion to begin at a much higher level than over a flat country.

Measurements over grass wet with dew show that the inversion there starts right from the surface. But on grass free from dew, the surface temperature is found to be higher than that of the air immediately above.

The data obtained by us so far have raised some interesting problems regarding the role of radiation from the ground and the lower layers of the atmosphere in determining the vertical distribution of temperature during clear nights. The subject is under enquiry.

Calcutta.

FIG 1. The brief paper of Ramdas and Atmanathan[1] containing the first reports of the lifted temperature minimum.

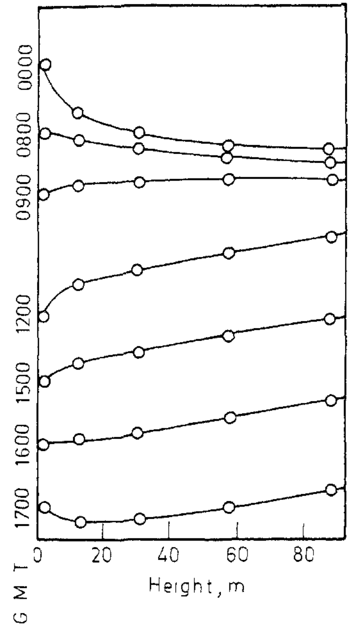

FIG 2. The air temperature profile near the ground at selected times during a 24-hour cycle (after Sutton[2]).

the layer and its thickness, shows it to be often two orders of magnitude higher than the critical value for plane convection between two horizontal plates, suggesting that the observed cold layer should be highly unstable. Finally, accurate temperature measurements near the ground present special problems, and hence it was not clear whether the instruments used by Ramdas were adequate. It is thus no surprise that, as Geiger[3] remarks in his monumental treatise *The climate near ground*, "These results were at first accepted with some reservations".

For a long time, the favoured explanation for these observations of the lifted minimum was that it must be due to advection, *i.e.*, flow of colder air from the environs. Ramdas continued his investigations of the phenomenon for several years (presumably outside working hours, for Prof. Pisharoty tells me that his employers used to require for a long time a certificate to that effect for any research work carried out by their staff, apparently to ensure that service functions did not suffer), and went on to become the father of agricultural meteorology in India, establishing a division in the India Meteorological Department devoted to its study (well ahead of any other country in the world). Although his later work showed the advection theory to be an unlikely explanation, it was not until the German meteorologist Klaus Raschke came all the way to India with his own radiation-compensated thermocouples and confirmed the existence of the lifted minimum[4] (Fig. 3), that the effect was accepted as genuine. Raschke made thorough and careful measurements of near-ground temperature distributions and of wind (Fig. 4), at a site on top of Chaturshringi Hill at Pune. This hill, which provides now a spectacular backdrop to the guest house of the National Chemical Laboratory, is remarkably bare and flat at the top, thus reducing the possibility of advection as a relevant factor at the site. That Raschke came all the way to India to make the measurements indicates that the phenomenon was thought to be peculiar to the tropics, as implied in the original paper of Ramdas and Atmanathan[1]. Ironically, within a short period of a few years in the 1950s, two decades after the first Indian reports, confirmation of the effect came from many parts of the world, including UK, USA, USSR, Argentina, Hungary, etc., establishing the fact that the phenomenon was not peculiar to the tropics. Indeed, the lifted minimum may well be responsible for the fairly common sight on cold mornings of a thin layer of fog suspended above the ground at a height of about half a metre.

It is remarkable that there has been no satisfactory explanation for the phenomenon till now.

It has been widely suggested that radiation is somehow responsible, but the first reaction of many experts to this suggestion is one of doubt, as there does not appear to be any obvious length scale of a metre or less in radiative transfer in the atmosphere. Others have suggested that convection and turbulence may play key roles.

METEOROLOGISCHE RUNDSCHAU

10. JAHRGANG JANUAR/FEBRUAR 1957 HEFT 1

ÜBER DAS NÄCHTLICHE TEMPERATURMINIMUM ÜBER NACKTEM BODEN IN POONA (INDIEN)*

Von

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Mit 17 Textabbildungen

Zusammenfassung

In Poona (Indien) wurden die Temperaturverhältnisse innerhalb der bodennahen Luftschicht (1 mm—10 m) mit Thermoelementen unter Kompensation des Strahlungsfehlers registriert. Die in 183 Nächten gemessenen Temperaturverteilungen uber nacktem, trockenem Boden lassen 3 Typen erkennen:

1. Ausstrahlungstypus mit Temperaturminimum am Boden. Tritt auf in klaren Nächten mit Wind.

mententechnischen Grunden können in nachster Bodennahe ähnliche Zustände vorgetäuscht werden."

Während eines Aufenthaltes an der agrarmeteorologischen Abteilung des indischen Wetterdienstes in Poona ergab sich die Moglichkeit zu einer solchen von *Geiger* geforderten Nachprüfung. Über die Ergebnisse soll im Folgenden berichtet werden.

Um durch Instrumente hervorgerufene Fehler zu vermeiden

FIG 3. Title of paper by Raschke[4]

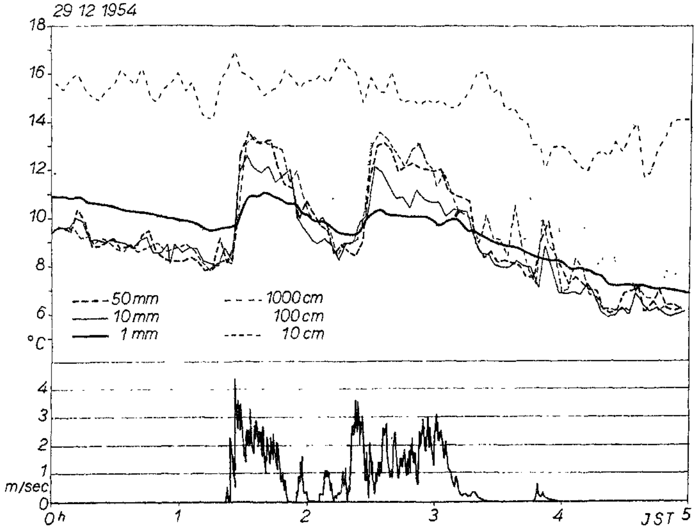

FIG 4. Raschke's measurements of temperature at different levels, and wind speed at a height of 20 cm, at a site on top of Chaturshringi Hill, Pune. Note the temperature minimum over the height range 10–100 mm, and how quickly it disappears if the wind picks up and reappears with calm.

although the lifted minimum is observed only on calm nights; Raschke could get rid of it by waving a lath board close-by (aerodynamicists would say that this 'trips' the flow to a turbulent state), but the minimum would reappear almost as soon as the tripping ceased: it therefore seems that even slight amounts of turbulent diffusion are enough to suppress the phenomenon, as Fig. 4 makes clear.

If radiation does play a role it must be subtle. To see this suppose the medium is optically thick, then a flux-gradient relation for radiative transfer would be valid, and the net effect on the energy balance would be the same as an enhancement of thermal diffusivity. It can, however, be shown that with diffusive transport the governing equation is parabolic and no lifted minimum can be sustained. If, on the other hand, the medium is optically thin, radiation just escapes across, and cannot affect the medium. Thus in neither of the two obvious limits can radiation explain the phenomenon. If, therefore, it holds the key, we must seek it in the thin-to-thick transitional domain, and in the peculiar properties of atmospheric absorption. Most of this is due to water vapour, but the absorptivity is a wild function of the wavelength; using the data listed by Kondratyev[5], for example, one finds that, at

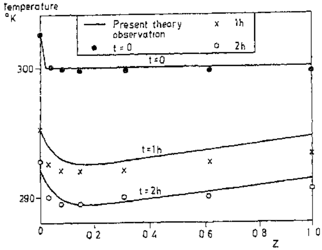

FIG 5. Variation of the flux emissivity of air with optical path and height. Note the steep rise to low path lengths, in what we call the 'emissivity sublayer'.

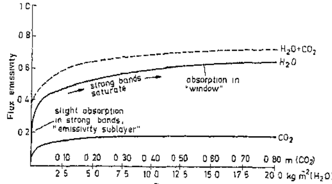

FIG. 6. Comparison of the temperature profiles computed through the present model with the observations of Ramanathan and Ramdas[1].

the typical water vapour density of 10^{-2} kg/m^3, the photon mean free path varies from a few metres in the strongly absorbing bands (wavelengths less than 8μ or greater than 20μ) to about ten kilometres within the atmospheric window (8–14μ). This wide range of lengths makes the optically thick and thin limits unrealistic. (Note, incidentally, that the lowest value of the mean free path, which is 5·05 m in the 6–6·5μ and 33–34μ bands, is still an order of magnitude larger than the typical height of the lifted minimum.)

The only quantitative model that purports to explain the phenomenon is due to Zdunkowski[6]. This model invokes a layer of haze, and generally predicts a temperature minimum near the top of the assumed haze layer. There are, however, two disturbing aspects of this theory. First of all, to obtain numbers of the kind observed, the total thermal diffusion has often to be taken as much less (by a factor of up to 18) than the molecular (that is classical non-turbulent) diffusion; but while one can conceive of suppressing turbulent transport, there is no way of doing that to molecular transport! Secondly, no haze layer of the type postulated has been reported under lifted-minimum conditions by later observers who were aware of the Zdunkowski theory.

We have recently completed extensive studies of a model that offers a logical explanation of the Ramdas effect[7]. This theory does not invoke a haze layer, but shows that two factors ignored in all previous explanations play key roles. One is surface emissivity (ε_g, say), and the second is soil conductivity. In meteorological investigations, it is usual to assume that the ground is radiatively black (*i.e.*, $\varepsilon_g = 1$); it is indeed nearly so, but the small departures present do matter for a special reason. The flux emissivity of the air, ε_a say, varies extremely rapidly with distance above the ground (z) as the water vapour present in air is a strong absorber (especially in the rotation bands); this variation is shown as a function of the optical path in Fig. 5 (adapted from Liou[8]), and incidentally reveals the existence of what we shall call an 'emissivity sublayer', whose thickness ($\approx$ 1m at a water vapour density of 10^{-2} kg/m^3) provides the missing length scale in the problem. The radiative cooling of air near the ground depends on the product

$$(1 - \varepsilon_g)\ [d\varepsilon_a/dz]_{z=0},$$

which cannot be ignored even if ε_g is close to unity, because the multiplying derivative is huge.

By the way, it is interesting to note that the standard screen height, that is the height at which the thermometers are mounted in the familiar meteorological station, is generally just above the emissivity sublayer. Whether by design or accident, or as a result of hard experience, this height is just enough to ensure that most of the time temperature readings are not strongly influenced by the vagaries of the ground surface, but one can imagine conditions under which this would not be true; so this is a question which calls for further investigation.

The second parameter in the model we have proposed, namely, soil conductivity, is important because it determines how fast the ground cools; higher the conductivity lower is the cooling rate, because of greater upwelling heat flux from warm soil underground.

The gist of the proposed theory can now be simply stated. When the ground is not perfectly black, air above the ground can cool radiatively because of the rapid variation (with height) of the absorption of infrared radiation by water vapour. Because of relatively long photon mean free paths at almost all wavelengths (not to mention the enormous values in the atmospheric window), a radiative slip at the ground will usually be present. The sign of this slip can be such that the ground is warmer if the soil is sufficiently conducting to keep the ground cooling slow. A touch of diffusion, chiefly only molecular, smears out the slip into the cold layer observed by Ramdas.

All of these effects have been incorporated into a detailed mathematical model; a comparison with the observations of Ramanathan and Ramdas[9] is shown in Fig. 6 and is about as good as can be expected in this kind of study. One of the predictions of the model is that the lifted minimum disappears if eddy transport exceeds some four times the molecular conduction, which is in broad general agreement with observation.

There remains the question of how the Rayleigh-Benard instability is circumvented. This must be largely an effect of radiation, for it is easy to see that radiation is stabilising. For a given temperature difference the presence of radiation adds to the heat transfer by conduction and so may be thought of as increasing the effective conductivity of the medium. This becomes literally true when the medium is nearly opaque, for then a radiative thermal diffusivity K_r can be formally introduced. It is reasonable to expect that a modified Rayleigh number, with $K_r + K_m$ replacing the molecular diffusivity K_m, would have the same critical value for instability as in the non-radiative situation, everything else remaining the same (which does not actually happen, but this makes no qualitative difference). The classical Rayleigh number (defined with (only) the molecular thermal diffusivity K_m in the denominator) will, therefore, have, with radiative diffusion, a critical value that is larger by a factor of order $(1 + K_r/K_m)$. This factor can be considerable (several orders of magnitude). When the medium is optically thin the argument is not strictly valid, but the additional transfer of heat by radiation should even then have the qualitative effect of stabilising the flow. A more rigorous assessment of the effect of radiation with the semi-open boundary conditions characteristic of the present problem is desirable, but estimates made by us (based on the arguments of Goody[10] and Vincenti and Traugótt[11], involving the ratio of diffusive and radiative time scales) indicate that the critical Rayleigh number can be raised by a factor of somewhere between 10 and 150. Furthermore, heat transfer rates increase rather slowly with Rayleigh number (like its cube root in the asymptotic limit), and attain four times the molecular conduction — when we may expect the minimum to be suppressed — only at a value of Rayleigh number about 60 times the critical, according to the comprehensive survey of experimental data undertaken by Hollands *et al*[12]. It thus seems that the answer to the puzzle of how the heavier fluid at the lifted minimum can sustain itself without overturning lies partly in radiative stabilisation, and partly in the no-more-than-modest increase in heat transfer even under highly super-critical conditions: the Rayleigh-Benard instability is either not operative at all or only weakly so.

There is one last bit of irony in the story, for the Poona data in the very first report of Ramdas and Atmanathan are almost certainly contaminated by advection, as the authors themselves suspected. Neither the height nor the intensity of this first observation of the lifted minimum, both substantially at variance with all later reports, can be reproduced by the present theory for any reasonable values of the model parameters.

The lifted minimum could have implications in agriculture and horticulture: there are reports of how, in tomato plants, frost first affects fruit well above the ground. There may be conditions when retrieval of surface temperatures by remote sensing techniques may have to account for the phenomenon.

The present theory predicts that the lifted minimum is weaker on rough, dark (radiatively, that is) and insulating ground. These predictions lend themselves to experimental checks, which, therefore, now become interesting to carry out.

Acknowledgements

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