Comparison of Aerological Soundings made Simultaneously by Radio-Sonde and Aircraft

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Abstract

On five separate occasions soundings were made at the same time by Väisälä radio-sonde and by an aircraft equipped with electrical resistance thermometers. Display of the results leads to the conclusion that the temperature indicated by the radio-sonde was too high by an amount which usually was between 1 and 1½° C, but occasionally reached 2½ to 3½° C. The usual difference can be accounted for by the known effects of lag and radiation error, and it is recommended that even in the lower troposphere appropriate corrections should be made as a routine in conditions of sunny weather and steep lapse rate. Because of the excessive lag often shown by the radio-sonde hygrometer unit (of hair), shallow layers of very dry air are not indicated at all in the radio-sonde soundings.

1. Introduction

It is well known that radio-sonde observations of temperature and humidity are subject to noticeable errors arising from the lag of the thermometer and hygrometer, and from the warming of the thermometer element which occurs when it, or its housing, is exposed to strong sunshine.

It is increasingly common practice to make corrections for these errors, but it is still widely believed that in the lower troposphere, where the sensing elements are fairly efficiently ventilated, the errors are unimportant. Certainly in routine synoptic analysis the significant errors are only those of one instrument with respect to the others used in the synoptic network, but in the analysis of individual soundings it may be necessary to consider the variation of the errors with height, or even the absolute values of the errors in the measurements made at particular levels. Such considerations are necessary, for example, for studies of cumulus growth and abnormal radio propagation, in which vertical gradients of temperature and humidity are important.

It is sometimes held that the existence of local variations of temperature and humidity render unnecessary the precise reporting of the sounding as recorded at the observing station, and even make corrections for lag and radiation of doubtful value. It is certainly true that the synoptic meteorologist involved in forecasting practice can hardly benefit from a study of the detail of soundings, nor can he afford to have his communication channels and plotting assistants overburdened with reports of such detail. Nevertheless the routine soundings contain a remarkable wealth of information for the meteorologist who studies meso-scale processes in the atmosphere and in our view it is unfortunate that often only

* The observations described were made during field work carried out while the writers were attached to the International Institute of Meteorology, Stockholm.

smoothed and partially corrected versions appear in published aerological records.

During our field work in Sweden, which was concerned mainly with the structure and growth of shower clouds, we were fortunate to have our ground observations supplemented by soundings made at the nearby radio-sonde station of Frösön, and by reconnnaissance flights of an aircraft of the Swedish Air Force, equipped with electrical resistance thermometers. It became apparent that their observations were not always in perfect agreement, and by the kind co-operation of both establishments we arranged for the aircraft to make some soundings in the vicinity of the radio-sonde station at the time of release of radio-sondes. We then compared the respective soundings and confirmed that the radio-sonde indicated temperatures which differed by amounts which are significant in our studies. Similar comparisons have been made by other investigators, but their results have not, to our knowledge, been given unrestricted publication, and so we believe that an account of our own work will be interesting.

2. The aircraft instrumentation

The aircraft was equipped with British Meteorological Office balanced bridge resistance thermometers, with knife-type wet- and dry-bulbs mounted in anti-radiation housings on the under-surfaces of the main wings. The thermometers are brought separately into the bridge circuit, and readings are made against a scale marked in Fahrenheit degrees upon a rheostat which is used to bring a galvanometer needle to a zero-point. A practised observer under normal flight conditions can read the scale with an accuracy of 0.2° F.

When a sounding was made the thermometers were read during level flight when two or three successive measurements at intervals of about 20 seconds had shown steady values to have been attained (the lag coefficient of these thermometers is known to be only a few seconds). It is necessary to apply corrections to the height indicated by the altimeter, and to the temperatures indicated by the thermometers.

Atmospheric pressure was determined from the reading of an ordinary aircraft altimeter, whose millibar sub-scale was set at 1,013.2 mb, so that the height-pressure relation was that of the I.C.A.N. atmosphere. From observations during flights made at a height of 25 m above the airfield barometer it was established that the position-error amounted to less than 1 mb. The altimeter was carefully calibrated against a mercury barometer; the departures of the indicated from the true I.C.A.N. height were less than 12 m (about 1 mb) at all heights up to 2 km, and increased from 20 m at 2,500 m to 35 m at 3,500 m: the appropriate corrections to the indicated heights were made during the evaluation of the soundings.

The indicated temperatures during flight exceed the true air temperatures by an amount $\Delta T°$ F which is related to the true air speed v km/hr by the equation

$$\Delta T = \alpha_D (\mathrm{v}/100)^2 \ldots\ldots\ldots \quad (1).$$

There is some evidence that the coefficient α_D is not constant, but a function of Reynolds Number at the thermometer bulb; however, during horizontal flights on two separate occasions at eight indicated air speeds ranging from 140 to 275 km/hr we found α_D practically constant and deduced values of α_D as 0.40 and 0.42. From calibration flights made the previous summer with a similar thermometer we had deduced a value of 0.40. We used a mean value of 0.41 for the new thermometer, and by a similar procedure derived another coefficient for correcting the temperatures indicated by the wet bulb. At the usual flight speed of 220 km/hr the corrections applied to the dry- and wet-bulb readings amounted to about 2° F. We believe that the deduced values of true air temperature and dew point are unlikely to have errors exceeding 0.5° F and 2° F, or about 0.3° C and 1° C, respectively.

3. Comparison of temperatures measured at the ground and during flight just above

At 0815 on 1 September 1955 the aircraft was flown over the airfield at an estimated height of 35—40 m above the ground. The indicated temperature was 53.9° F and the corrected value 51.1° F, or 10.6° C. At the same time an observer on the ground measured a temperature of 11.0° C with an Assmann pyschrometer. The surface wind was NW, 5—7 m/sec, and the sky was overcast with stratus layers; the lowest clouds were 2/8 stratus fractus with base 300 m above the airfield. The convective condensation level was deduced from the Assmann readings to be at 320 m. It is therefore reasonable to suppose a dry adiabatic lapse-rate near the ground and to deduce a temperature of about 10.6° C at the flight-level, in agreement with the value obtained from the aircraft thermometer. The exact correspondence is perhaps fortuitous and we had no opportunity to make other tests, but believe this result justifies our confidence in the temperatures deduced on the aircraft soundings.

4. Comparison of aircraft and radio-sonde soundings

Aircraft soundings were made for comparison with 3 routine and 2 special soundings by Väisälä radio-sonde. The results are represented on *T-Φ* diagrams in Figs 1 to 5. All the soundings were made in fair weather, when there was little or no cloud.

It will be observed in Figs. 2 and 5 that on occasions of the special radio-sonde ascents there is a quite remarkable similarity in the trend of the temperature curves obtained by the two methods. The same feature is less strikingly displayed on the remaining occasions, and strongly indicates that the soundings are equally representative of the atmosphere in the neighbourhood of the radio-sonde station, and that the differences between the simultaneous soundings cannot be attributed to purely local temperature variations.

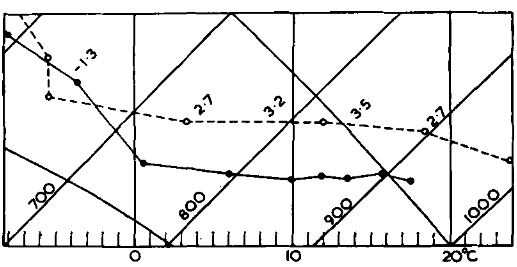

Figure 1. Comparison soundings (dry bulb only), 15 Aug. 1955. The pecked curve shows the record of the radiosonde, the full line that of the aircraft sounding. The figures beside the pecked curve indicate the differences between the temperatures at particular levels.
The radiosonde was released at 1530 local time and the aircraft sounding was made between 1455 (highest level) and 1515 (lowest level). There were scattered Cumulus with base 760 mb and tops to 550 mb.

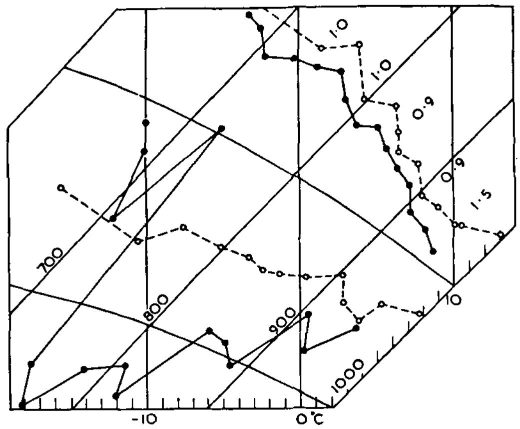

Figure 2. Comparison soundings (including dew points), 22 August 1955. The radiosonde was released at 1040 and the aircraft sounding was made between 1020 (lowest level) and 1114 (highest level). There was less than $^{1}/_{8}$ Cumulus with base 910 mb and tops to 880 mb.

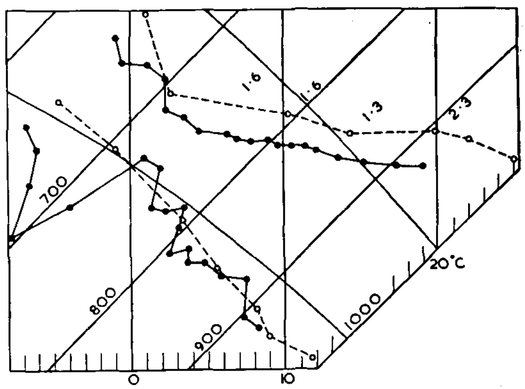

Figure 3. Comparison soundings, 25 August 1955. The radiosonde was released at 1530, and the aircraft sounding was made between 1508 (lowest level) and 1605 (highest level). There was less than $^{1}/_{8}$ Cumulus with base 800 mb and tops to 770 mb.

The diagrams also show that the radiosonde consistently records higher temperatures, the difference amounting to between about 1.0 and 3.5° C and tending to be greater when the lapse-rate has a high value. The largest differences occur on two afternoons when the radio-sonde indicates a lapse-rate near the ground (Figs. 1, 3) which is *less* than the dry adiabatic, whereas under these conditions a superadiabatic lapse rate would be expected, and is indeed found by joining the points representing surface conditions to those corresponding to the measurements made in the aircraft at its lowest flight level.

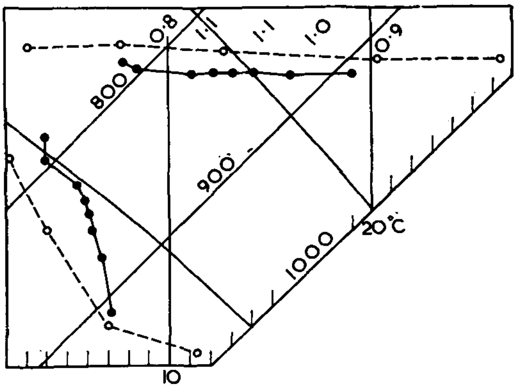

Figure 4. Comparison soundings, 26 August 1955. The radiosonde was released at 1530, and the aircraft sounding was made between 1515 (lowest level) and 1535 (highest level). There was less than $^1/_8$ Cumulus with base 776 mb and tops to 690 mb.

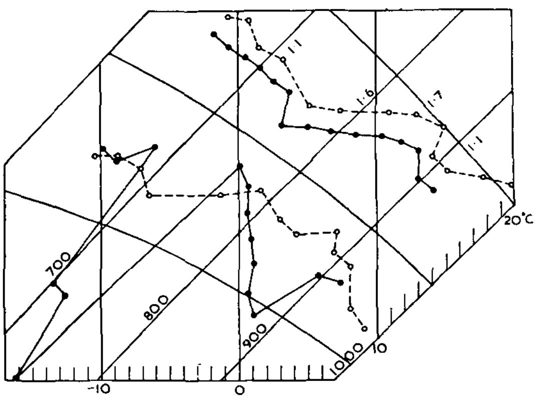

Figure 5. Comparison soundings, 27 August 1955. The radiosonde was released at 1111 and the aircraft sounding was made between 1059 (lowed level) and 1135 (highest level) in a cloud-free sky.

Consequently there is good reason to believe that in these conditions the radio-sonde temperatures are too great, by 1.0 to 3.5° C.

On the four occasions when comparisons of dew-points can be made the respective soundings are in reasonable agreement near the ground. The general agreement up to 3 km on 25 August 1955 (Fig. 3) is striking, but on other occasions the aircraft sounding tends to indicate dew points which are lower than those on the radio-sonde record. In particular the radio-sonde fails to portray rather shallow layers of very dry air, which are a feature of 3 of the aircraft soundings (Figs 2, 3 and 5).

5. Discussion

On all occasions there was strong sunshine, and it is reasonable to attribute the errors in the records of the radio-sondes to the combined effects of radiation and lag.

NYBERG (1940) has measured the lag coefficient α of the Väisälä radio-sonde at different ventilation speeds under room pressure and has found a mean value of 15 sec. for its usual speed of ascent through the atmosphere. If the rate of change of temperature is β and is constant, the radio-sonde thermometer records a steady-state temperature which is too high by an amount $\alpha\beta$. If therefore v is the speed of ascent (relative to the ground) of a radio-sonde through air with a lapse-rate γ, the steady-state temperature error is $\alpha\, v\, \gamma$. The speed v in still air is usually about 6 m/sec, so that the error due to lag during rise through air having a dry-adiabatic lapse rate can be expected to be about $6 \times 10 \times 10^{-2}$ ° C, that is, about 0.9° C. On occasions when the lapse rate is a fraction of the dry adiabatic, the error is correspondingly reduced, and becomes zero in an isothermal layer.

On the other hand the maximum computed error due to lag may be considerably increased on occasions owing to the use of a thermometer element having a lag coefficient greater than the average, and possibly it can be further increased when the balloon enters a thermal. The speed of ascent may then be increased by up to 100 %, with a corresponding increase of the lag error; moreover the balloon may then be in air which has a temperature a few tenths of a degree Centigrade higher than the mean temperature over distances of more than a kilometre, which is that determined by the aircraft. Consequently the total discrepancy due to these two effects could then conceivably attain 2.0° C.

The error due to sunshine falling upon the radiation shield of the thermometer is known to amount to about 1° C at a height of 10 km when the sun has an elevation of 25—30° (as during the comparison soundings), but is usually regarded as negligible in the lower troposphere. In the evaluation of the Väisälä radio-sonde records it is assumed to be zero below the 500 mb level, for there clouds frequently and effectively shield the thermometer from sunshine. However, at the solar elevations mentioned and at the 800 mb level the formulae for radiation error in clear skies given by VÄISÄLÄ (1941) and by RAUNIO (1951) give a value of about 0.5° C, and for similar conditions SCRASE (1954) calculates a radiation error of about 0.5° C for the British radio-sonde, on which the thermometer element is protected by a shield of the same kind as that used on the Väisälä radio-sonde.

It therefore appears that the discrepancies found during the comparison soundings can on the whole be accounted for by the combined errors known to be due to the effects of lag and radiation. It is possible that on the occasion of the excessive differences shown in Fig. 1 some contribution was also made by two sources of error mentioned by NYBERG (1952): inaccurate corrections made when measuring temperatures at the ground just before the release of the radio-sonde, and minor shocks during the release.

Since sunny weather and strong lapse rates are not altogether uncommon, and result in radio-sonde temperatures which are too high by more than 1° C, we recommend that appropriate corrections should be made in these circumstances for the effects of lag and radiation even in the lower troposphere.

The lag of most hygrometer elements is so great that the record of relative humidity provided by the radio-sonde cannot be expected to represent such sudden changes as may actually be encountered. In particular the remarkable shallow layers of very dry air which are recorded during some aircraft soundings are not revealed at all. HOOPER (1957) has recently commented upon the variable qualities of radio-sondes in their capacity to detect strong gradients of vapour pressure, which are important in the study of radio wave propagation. As water vapour plays such an important part in atmospheric behaviour, and as changes in its concentration are a sensitive indicator of atmospheric processes, we hope that a solution will soon be found to the old problem of devising a hygrometer element with a rapid response, or some means of correcting its indications for the errors due to excessive lag.

Acknowledgements

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REFERENCES

HOOPER, A. H., 1957: Heterogeneity in the measurements of humidity made by the radio-sonde network of Europe, *Met. Mag.*, **86**, p. 13.

NYBERG, A., 1940: The lag coefficient of aerological instruments and the function of hair hygrometers at low temperatures, *Medd.*, Ser. Upps. No. 32, S.M.H.I., Stockholm.

— 1952: On the comparison of radio-sonde data in Payerne, May 1950, *ibid.* Ser. B., No. 9.

RAUNIO, N., 1951: Amendments to the computation of the radiation error of the Finnish (Väisälä) radio-sonde, *Geophysica* **4**, p. 14.

SCRASE, F. J., 1954: Radiation and lag errors of the M. O. radio-sonde and the diurnal variation of upper-air temperature, *Quart. J. R. Met. Soc.*, **80**, p. 565.

VÄISÄLÄ, V., 1941: Der Strahlungsfehler der finnischen Radiosonde, Univ. of Helsinki, Inst. of Met., *Mitt.* No. 47.