# Richard Assmann's Discovery of the Stratosphere

Thomas Birner*

*Colorado State University, Fort Collins, CO, USA,*

*now at: Ludwig-Maximilians University Munich, Germany*

**Corresponding author address:* Meteorological Institute, Ludwig-Maximilians University Munich, Theresienstr. 37, 80333 München, Germany

E-mail: thomas.birner@lmu.de

# ABSTRACT

no abstract

## 1. Notes on Translation

- **Disclaimer:** I'm not a professional translator, so if some passages are unclear it may be due to my limited abilities as a translator rather than Assmann's original formulations. Comments and/or suggestions are certainly welcome!

- Some German references on Assmann use the spelling "Aßmann" despite the fact that, as far as I can tell, he appears as "Assmann" in his original publications (all written in German). Here we consistently follow the latter spelling.

- Paragraphs are numbered to ease possible later discussion.

- The translation is not strictly literal in some places, but leaves all of Assmann's original sentences and formulations intact, including his many complexly nested, and hence hard to follow, albeit this having been standard at the time and fortunately is generally avoided today, with the exception of occasionally making a point, sentences.

- Assmann's term "thermal gradient" ("thermischer Gradient") refers to what is now known as the "lapse rate" and has been translated as such throughout.

- Throughout his report, temperatures are given in degrees Celsius, however, often without explicit mentioning of the unit.

- All references are provided as footnotes, as in the original report, with english translations italicized and given in parenthesis.

## 2. Translation of Assmann's 1902 report to the German Academy of Science: "On the existence of a warmer air flow at heights from 10 to 15 km"

[1] Recent studies on the vertical distribution of temperature in the atmosphere have produced proof that the gradual decline of its decrease with rising elevation, as found by James Glaisher, rests on a fundamental error of his methods and instruments: on the contrary a general increase of the lapse rate with height resulted, in accordance with the laws of the mechanical theory of heat.

[2] Moreover, a pronounced lamination within the ocean of air was identified, which is closely related to cloud formation as well as horizontal and vertical air flows.

[3] According to the accounts of Messrs. Berson and Süring in the third volume of the report "Scientific Aviation", the direct observations from the manned free balloon reaching up to a height of 9,000 m yielded four layers of air, well characterized by peculiarities of their temperature, humidity, and motion, with the highest being characterized by a nearly adiabatic temperature decline, small water vapor content, and substantial wind speeds.

[4] Soon after the identification of the large temperature decrease of the higher atmospheric layers, which amounts to nearly one degree per 100 m rise, Mr. Berson, who had primarily ascertained this fact, pointed out in his work on the temperature of the air[1], that the continuation of this strong temperature decline must lead to the temperature of absolute zero, that is $-273°$, at heights of about 30 km. A diminished lapse rate at larger elevations and an asymptotic approach to a lower threshold value should therefore be considered indispensable.

[5] Likewise, he and after him Mr. von Bezold[2] rightly pointed out that the notion of "air temperature" becomes generally invalid at further distances from the Earth, and that even at the

[1]Assmann und Berson, Wissenschaftliche Luftfahrten, Braunschweig 1901, Friedr. Vieweg u. Sohn, Bd. III, S. 67 (*Assmann and Berson, Scientific Aviation, Braunschweig 1901, Friedr. Vieweg and Sons, Vol. III, p. 67*)

[2]Ibid. Bd. III, S. 295 (*Ibid. Vol. III, p. 295*)

most extreme dilution only heat absorption and emission of the thermometric body come into consideration, whereas heat conduction recedes exceedingly.

[6] On the other hand, the multiple detected cirrus clouds at heights from 10 to 15 km suggest that by no means this diluted state has been reached at these regions, the more so as sufficient water vapor and dust particles exist there in order to form these cloud structures.

[7] It was now learned, following the procedure of Hermite and Besancon in Paris, to send small balloons aloft to the heights in question, only carrying recording instruments, and one had to expect a solution of this important question from these recordings.

[8] Indeed, already the first attempts of this kind allowed to discern not only a decline of the temperature decrease at the greatest heights, but even an extraordinary increase, which for some ascents amounted to 30° and more. Soon however, under the same consideration that unfortunately took away the success of Glaisher's unsurpassable observations, they were identified as a product of insolation and thence as erroneous.

[9] Obviously, for a balloon left by itself with invariant volume, whose uplift steadily diminishes before it reaches its equilibrium position, the natural ventilation of the carry-on apparatus must decrease in precisely the same amount, hence growing the insolation influence whose intensity in any case grows considerably with height. If the balloon then floats at the same height for hours, as has been found at many such balloon ascents, the effect of the insolation on the thermometer accumulates up to some limit, forcing it to values that lack any relation to the temperature of the surrounding air.

[10] In order to avoid this perversive insolation effect, experiments have been conducted with the goal of either allowing sufficient artificial aspiration at even the greatest heights, or seeking to be free from solar radiation by rescheduling the ascents into the night.

[11] The former approach did not succeed, because aspiration devices that work continuously and sufficiently under the extraordinary conditions at great heights could not be constructed. The nighttime ascents, however, necessarily provided a biased picture of the lower atmospheric layers and one did not wish to do without the simultaneous exploration of those layers.

[12] The author, who has contributed to this important problem avidly right from the beginning, and who was the first to point out the inadmissibility of viewing the detected high temperatures as real and the advantages of the nighttime ascents, has tried to overcome the difficulties of this task ever since the foundation of the Aeronautical Observatory of the Royal Meteorological Institute.

[13] A sealed balloon with variable volume, e.g. made from an elastic para rubber, rises with its initial ascent rate until it bursts: it therefore does not approach an equilibrium position.

[14] Upon more detailed consideration, however, one finds that its ascent rate must in fact increase considerably, as the air density decreases faster than its surface area increases: hence, the aerodynamic drag it experiences must decrease; in fact, a calculation, which will not be detailed here, reveals that the ascent rate increases roughly proportional to the diameter of the balloon. At a pressure of 95 mm, corresponding to an eighth atmosphere and near 15,000 m altitude, the diameter of the rubber balloon has doubled compared to when it left the surface, and its vertical velocity has nearly doubled as well: if given an initial ascent rate of 5 m/s by filling a corresponding amount of gas, it will amount to 10 m/s at 15 km altitude.

[15] Further, by arranging the thermometer such that it is protected against direct insolation by a high-gloss polished double tube, analogous to the established method of the aspiration thermometer, and by providing the balloon with an ascent rate such that a strong airstream, strong enough so that any radiation influence is eliminated with certainty, is directed past the bell-mouthed radiation-protected tube, open at the top and bottom, and its enclosed thermometer element, then this "natural ventilation" will be effective during the entire ascent and up to the greatest heights.

[16] As soon as the balloon bursts it begins to fall, which conveniently is checked by a small parachute, enough so that the apparatus arrives at the Earth's surface without serious damage. In this case, the above sequence is reversed with a fast fall at greater altitudes and a slowed fall with increasing air density.

[17] One easily recognizes the main advantages of the latter method by realizing that a ventilation takes place, which grows in the same sense as the radiation intensity, both during ascent and descent, while for a balloon of invariant volume the ventilation is reduced and eventually becomes zero where the radiation intensity reaches its maximum corresponding to the gained altitude.

[18] Examining the recordings retrieved from such rubber balloons for all cases for which altitudes of 10 km were exceeded, revealed signatures for the existence of a temperature inversion above this limit, the detection and discussion of which is the purpose of this publication.

[19] The analyzed temperatures at steps of 500 m altitude of those 6 registration balloon ascents of the year 1901, whose altitude reached or exceeded 12 km, are compiled in the adjacent table. Note that these do not represent a selection out of many such high-reaching ascents, rather a larger number is not yet available. Next to the temperature data in the table, in the column $\Delta t$ per 100 m, are the accompanying values of the temperature changes over 100 m elevation found between the individual levels; the negative signs correspond to a decrease, the positive to an increase of the temperature with altitude.

[20] One notes firstly that for the ascents of July 4th and August 1st, an increase of temperature with altitude took place in the lowest levels, and as can be seen from the enclosed ascent times, one notes that this phenomenon is exclusively peculiar to the early morning hours before sunrise: it represents a result of the clear sky radiative surface cooling.

[21] At levels above 1,000 m altitude this temperature inversion is not found anymore in our series, though repeated small – nearly isothermal – lapse rates between considerably larger ones

are found: these constitute the thermal laminations of the atmosphere and mostly coincide with the upper boundary of clouds. They are peculiar to the lower and middle layers.

[22] At more substantial elevations – above 5 to 7 km – the lapse rates generally become more uniform and significantly larger, in some cases the adiabatic limit for dry air, 1° per 100 m, is exceeded, and this takes place exclusively at greater heights, between 6 and 10 km.

[23] Above this zone of extraordinarily strong thermal decline, a new regime begins, immediately evident, which reveals itself through either a rapid attenuation of the lapse rate to the point of isothermal behavior, or an occurrence of a more or less intense temperature inversion.

[24] Let us now examine the individual ascents more closely from this viewpoint.

[25] On April 10th, above relatively small lapse rates that remained below the adiabat for snow, a temperature inversion began rather abruptly at a height of 10 km; at 10,500 m its magnitude was largest and decreased quite evenly toward isothermal behavior up to a height of 13 km. At this point, the obtained temperature of $-35°$ was equal to one recorded earlier at 7,800 m, and it was 9.4° higher than the one recorded at 9,500 m. It may be concluded from the very steady reduction of the positive decline, that full isothermal behavior would have been encountered at 15 km, and that at 18 to 19 km the temperature of 9,500 m altitude would perhaps have been encountered, if the balloon had reached further.

[26] In the present case, in contrast to all following, the rubber balloon, which had a diameter of only 1,200 mm, did not burst; rather it obtained an equilibrium position, albeit short-lived, at which it drifted northeastward at a speed of about 40 m per second. The corresponding plotted curve allows the instructive identification of the powerful insolation influence in that the temperature rose to $-24°$ during the time of lacking vertical motion and ventilation, however, during the gradually faster fall, due to leaking gas, the temperature closely followed the trace of the recorded ascent.

[27] On July 4th, a temperature inversion with a gradient of $+0.34°$ at 11 km began above an exceptionally fast decrease between 9,000 and 10,500 m altitude; this gradient then increased to $+1.0°$ and dropped back to $+0.3$ and $+0.1°$ at a height of 12 km. As in the previous case, one may suspect an isothermal layer near 14 km and the recurrence of the unusually low temperature of the lower boundary of the inversion – nearly $-60°$ – at 16 to 17 km. The highest recorded temperature was $7.7°$ above the lowest one found beneath.

[28] In this case, the balloon, which had a diameter of 1,500 mm, undoubtedly burst at the highest altitude, as can be seen with certainty from the trace crossings in the descent graph; as has been found experimentally, these arise due to the flapping of the balloon material, which hangs on the parachute as a shapeless cloth and, preventing its consistent unfolding, generates strong vacillations of the apparatus.

[29] On July 11th, a rubber balloon with a diameter of 1,800 mm was used, filled with 4 cubic meters of hydrogen gas; however, due to its strongly delayed ascent, diffusion must have deteriorated its gas so much so, that it ascended at only moderate rate. After it had encountered an exceptionally strong temperature decline at heights between 7 and 8 km, this decline reduced considerably with some fluctuations starting at a height of 10 km and transitioned to complete isothermal behavior between 11 and 12 km: because of its early burst here, the balloon did not reach the inversion layer that was probably located at higher altitudes.

[30] On July 31st, the day of the grand balloon flight by Messrs. Berson and Süring that reached a height of almost 11,000 m, i.e. up to our critical inversion layer – unfortunately no observations are available because both researchers were unconscious at these heights – another rubber balloon with a diameter of 1,800 mm ascended. On this unusually warm day the laminations reached up to great heights and this was also noted by the observers aboard the free balloon. The lapse rate did not exceed the adiabatic limit near 10 and 11 km, above that, however, it rapidly decreased

toward isothermal behavior near 12 km, then transitioning into an extremely uniform temperature increase of 5.2° reaching up to a height of 15,000 m. Unfortunately, at this point the recording pen left the paper at its upper edge, such that those given values in the table must be considered as hypothetical. However, a 2.5° lower temperature was recorded during the re-entry of the curve on the recording paper, undoubtedly following the burst of the balloon, and this allows one to conclude with high probability that the balloon indeed approached the upper limit of the warmer air flow, at which a 2.5° lower temperature revealed the transition to another negative gradient. A casual extrapolation across and beyond the missing part between both curves gives a likely height of 17 to 18 km.

[31] On the next day, August 1st, another rubber ballon of equal size was released, which however already burst near 13 km. It obtained between 9 and 11 km altitude a temperature decline exceeding the adiabat, but which rapidly reduced up to 12 km, and above that abruptly transitioned to a strong temperature inversion with an obtained magnitude of only 5.2°, because the balloon did not reach higher altitudes.

[32] At last on November 7th, a rubber balloon with a diameter of 1,800 mm encountered relatively minor laminations at lower and intermediate heights, with a very strong temperature decrease near 6 km, which, with minor fluctuations reached up to 8,500 m, where it rapidly diminished to give way to a complete isothermal behavior near 10 km. At 11,500 m there appears to be the onset of a small temperature increase, which however was not investigated further because the balloon burst at 12 km.

[33] If we now try to visualize the conditions as they may have existed in the upper atmospheric layers on these 6 days, then, accepting with the author the records to be unaffected by insolation, one has no other choice than to regard the existence of a considerably warmer air flow above the zone from 10 to 12 km as proven.

[34] However, it should not be left unmentioned that likewise Mr. Teisserenc de Bort in Paris, who, at his Observatoire de la météorologie dynamique in Trappes, has sent aloft about 500 registration balloons – called Ballons-sondes there, has provided evidence for an attenuation of the lapse rate above 10 km a few months ago. In a recently published communication[3], he calculates the thermal gradient of this altitude as $-0.3°$ per 100 m and determines that this regime begins at 10 km altitude for cyclonic weather type and at 13 km for anticyclonic weather type.

[35] Because his balloons – he exclusively uses those made of paper with a volume of 50 to 60 cubic meters – exhibit the above mentioned drawbacks of slowed ascent with increasing height and hence an approach to an equilibrium position, a proof of the lacking influence by radiation can only be brought about for those ascents that reached its highest altitudes at night. However, due to the substantially longer time that it takes the balloon to approach its equilibrium position in order to reach its greatest height, this condition can only be considered as fulfilled, if the ascent started 3 to 4 hours before sunrise, or, using an alarm clock as has been proposed by the author, if the ascent is aborted substantially below its maximum height.

[36] As pleasing as the confirmation of the obtained results is by the present author, using his undoubtedly advantageous method, it should be pointed out that his results represent a substantial step forward in that he could not only find a reduced lapse rate, but an increase of the temperature itself and hence the existence of a warmer air flow, and in some cases explore its upper boundary.

---

[3] Annuaire de la société météorologique de France 50, 1902, p. 49 (*Annual report of the French meteorological society 50, 1902, p. 49*)

[37] Mr. Teisserenc de Bort added to the four thermal layers, mentioned at the beginning of this report, a fifth; our experiments not only confirmed this layer, but identified it essentially as an absolutely warmer flow; furthermore, above it a sixth layer has been found with a return to temperature decline.

[38] A discussion of the causes of this warm flow may still be premature: it seems suggestive to address it as part of the undoubtedly existing large-scale atmospheric circulation, which mediates the upper branch of the air exchange between the equator and the poles. If the air masses, which have ascended to great heights above the tropical oceans and are relatively warm due to the steady condensation of their water vapor, flow along a downward sloping path toward the poles, then their heat loss due to conduction and radiation would be compensated by the dynamical process while sinking, and they would penetrate toward higher latitudes as a relatively warm flow.

[39] However, due to the so far unmentioned fact that a high-level cirrus deck was detected for several of our ascents at approximately equal height, it is further suggested that a causal relationship exists between this cirrus deck and our layer of discontinuity. Recent research has undoubtedly shown that perhaps all compact cloud decks at the various heights coincide with discontinuities, which may either be a product of the unstable equilibrium induced by the discontinuity together with billow formation, following the brilliant theory of Hermann von Helmholtz, or the zones of higher temperatures may create a condensation limit for the ascending air masses, as demonstrated by Berson and Süring. Applying these empirical results to the here established quite substantial discontinuity at great heights, no reason exists to doubt the possibility of such a relationship.

[40] It should not be forgotten, however, that at a height of 10 km, with the dominant low temperatures there, the adiabat for the snow phase is between 0.8 and 0.9° per 100 m, values

which have been found at these heights. Perhaps the warm air flow originating above tropical oceans contributes water vapor for the condensation, resulting in the high-level cirrus clouds.

[41] Given the presently existing uncertainties regarding the causes of formation of these cloud structures, any contribution to their closer investigation should be considered welcome. Perhaps one will then be able to distinguish more sharply high-level cirrus, which are a product of the upper general circulation and with it drift primarily from the west, and lower cirrus, which bear a causal relationship with the pressure centers of the lower and middle regions. The frequently used expression “false cirrus” already suggests a fundamental distinction based on their shape.

*Acknowledgments.* ERA-20C data used in Fig. 1 for comparison was provided by ECMWF through their data server. 20-CR data used in Fig. 1 for comparison was provided by NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, through their data server. TB gratefully acknowledges support by the Climate Dynamics Program of the U.S. National Science Foundation under grant 1151768.

# LIST OF TABLES

TABLE 1. Temperatures and thermal gradients ($\Delta t$ per 100 m) for registration balloon ascents, in steps of 500 m height.

| Altitude above sealevel | April 10th 1901 $11\frac{1}{2}$ a.m. | | July 4th 1901 $2\frac{3}{4}$ a.m. | | July 11th 1901 $8\frac{1}{4}$ a.m. | |
|---|---|---|---|---|---|---|
| m | C | $\Delta t$ per 100 m | C | $\Delta t$ per 100 m | C | $\Delta t$ per 100 m |
| 40 | 12.0° | | 11.4° | | 19.6° | |
| | | −0.74° | | +0.35° | | −0.43° |
| 500 | 8.6° | | 13.0° | | 17.6° | |
| | | −1.12° | | −0.22° | | −0.32° |
| 1,000 | 3.0° | | 11.9° | | 16.0° | |
| | | −0.44° | | −0.52° | | −0.28° |
| 1,500 | 0.8° | | 9.3° | | 14.6° | |
| | | −0.56° | | −0.82° | | −0.66° |
| 2,000 | −2.0° | | 5.2° | | 11.3° | |
| | | −0.46° | | −0.64° | | −0.36° |
| 2,500 | −4.3° | | 2.0° | | 9.5° | |
| | | −0.60° | | −0.42° | | −0.38° |
| 3,000 | −7.3° | | −0.1° | | 7.6° | |
| | | −0.54° | | −0.64° | | −0.72° |
| 3,500 | −10.0° | | −3.3° | | 4.0° | |
| | | −0.64° | | −0.34° | | −0.44° |
| 4,000 | −13.2° | | −5.0° | | 1.8° | |
| | | −0.72° | | −0.64° | | −0.56° |
| 4,500 | −16.8° | | −8.2° | | −1.0° | |
| | | −0.70° | | −0.62° | | −0.70° |
| 5,000 | −20.3° | | −11.3° | | −4.5° | |
| | | −0.52° | | −0.66° | | −0.80° |
| 5,500 | −22.9° | | −14.6° | | −8.5° | |
| | | −0.40° | | −0.76° | | −0.60° |
| 6,000 | −24.9° | | −18.4° | | −11.5° | |
| | | −0.54° | | −0.78° | | −0.56° |
| 6,500 | −27.6° | | −22.3° | | −14.3° | |
| | | −0.60° | | −0.80° | | −0.94° |
| 7,000 | −30.6° | | −26.3° | | −19.0° | |
| | | −0.58° | | −0.74° | | −1.60° |
| 7,500 | −33.5° | | −30.0° | | −27.0° | |
| | | −0.62° | | −0.80° | | −1.10° |
| 8,000 | −36.6° | | −34.0° | | −32.5° | |
| | | −0.46° | | −0.68° | | −1.46° |
| 8,500 | −38.9° | | −37.4° | | −39.8° | |
| | | −0.68° | | −0.88° | | −0.96° |
| 9,000 | −42.3° | | −41.8° | | −44.6° | |
| | | −0.42° | | −0.94° | | −0.84° |
| 9,500 | −44.4° | | −46.5° | | −48.8° | |
| | | +0.24° | | −1.40° | | −0.44° |
| 10,000 | −43.2° | | −53.5° | | −51.0° | |
| | | +0.54° | | −1.24° | | −0.46° |
| 10,500 | −40.5° | | −59.7° | | −53.3° | |
| | | +0.32° | | +0.34° | | −0.70° |
| 11,000 | −38.9° | | −58.0° | | −56.8° | |
| | | +0.24° | | +1.00° | | −0.44° |
| 11,500 | −37.7° | | −53.0° | | −59.0° | |
| | | +0.22° | | +0.30° | | 0.0° |
| 12,000 | −36.6° | | −51.5° | | −59.0° | |
| | | +0.18° | | +0.10° | | 0.0° |
| 12,500 | −35.7° | | −52.0° | | −59.0° | |
| | | +0.14° | | | | |
| 13,000 | −35.0° | | | | | |
| 13,500 | | | | | | |
| 14,000 | | | | | | |
| 14,500 | | | | | | |
| 15,000 | | | | | | |
| 15,500 | | | | | | |
| 16,000 | | | | | | |
| 16,500 | | | | | | |
| 17,000 | | | | | | |
| 17,500 | | | | | | |

TABLE 2. Temperatures and thermal gradients ($\Delta t$ per 100 m) for registration balloon ascents, in steps of 500 m height.

| Altitude above sealevel | July 31st 1901 $10\frac{1}{4}$ a.m. | | August 1st 1901 $3\frac{1}{2}$ a.m. | | November 7th 1901 $6\frac{1}{4}$ a.m. | |
|---|---|---|---|---|---|---|
| m | C | $\Delta t$ per 100 m | C | $\Delta t$ per 100 m | C | $\Delta t$ per 100 m |
| 40 | 23.0° | −0.87° | 15.1° | +1.17° | 6.5° | −0.48° |
| 500 | 19.0° | −0.92° | 20.5° | +0.02° | 4.3° | −0.44° |
| 1,000 | 14.4° | −0.78° | 20.6° | −0.62° | 2.1° | −0.76° |
| 1,500 | 11.0° | −0.56° | 17.5° | −0.68° | −1.7° | −0.68° |
| 2,000 | 8.2° | −0.44° | 14.1° | −0.12° | −5.1° | −0.42° |
| 2,500 | 6.0° | −0.34° | 13.5° | −0.30° | −7.2° | −0.40° |
| 3,000 | 4.3° | −0.26° | 12.0° | −0.28° | −9.2° | −0.60° |
| 3,500 | 3.0° | −0.44° | 10.6° | −0.36° | −12.2° | −0.46° |
| 4,000 | 0.8° | −0.52° | 8.8° | −0.76° | −14.5° | −0.52° |
| 4,500 | −1.8° | −0.56° | 5.0° | −0.52° | −17.1° | −0.46° |
| 5,000 | −4.6° | −0.68° | 2.4° | −0.48° | −19.4° | −0.72° |
| 5,500 | −8.0° | −0.70° | 0.0° | −0.60° | −23.0° | −0.76° |
| 6,000 | −11.5° | −0.44° | −3.0° | −0.76° | −26.8° | −1.14° |
| 6,500 | −13.7° | −0.62° | −6.8° | −0.74° | −32.5° | −1.20° |
| 7,000 | −16.8° | −0.72° | −10.5° | −0.50° | −38.5° | −1.00° |
| 7,500 | −20.4° | −0.60° | −13.0° | −0.74° | −43.5° | −0.70° |
| 8,000 | −23.4° | −0.74° | −16.7° | −0.80° | −47.0° | −1.08° |
| 8,500 | −27.1° | −0.78° | −20.7° | −0.76° | −52.4° | −0.86° |
| 9,000 | −31.0° | −0.72° | −24.5° | −0.90° | −56.7° | −0.28° |
| 9,500 | −34.6° | −0.76° | −29.0° | −1.00° | −58.1° | −0.04° |
| 10,000 | −38.4° | −0.88° | −34.0° | −1.00° | −58.3° | +0.02° |
| 10,500 | −42.8° | −0.60° | −39.0° | −1.26° | −58.2° | 0.0° |
| 11,000 | −45.8° | −0.84° | −45.3° | −0.94° | −58.2° | 0.0° |
| 11,500 | −50.0° | −0.54° | −50.0° | −0.80° | −58.2° | +0.02° |
| 12,000 | −52.7° | −0.30° | −54.0° | +0.80° | −58.1° | |
| 12,500 | −54.2° | +0.24° | −50.0° | +0.44° | | |
| 13,000 | −53.0° | +0.20° | −47.8° | | | |
| 13,500 | −52.0° | +0.20° | | | | |
| 14,000 | −51.0° | +0.20° | | | | |
| 14,500 | −50.0° | +0.20° | | | | |
| 15,000 | −49.0° | 0.0° | | | | |
| 15,500 | −49.0° | −0.16° | | | | |
| 16,000 | −49.8° | −0.14° | | | | |
| 16,500 | −50.5° | −0.26° | | | | |
| 17,000 | −51.8° | −0.14° | | | | |
| 17,500 | −52.5° | | | | | |

# LIST OF FIGURES

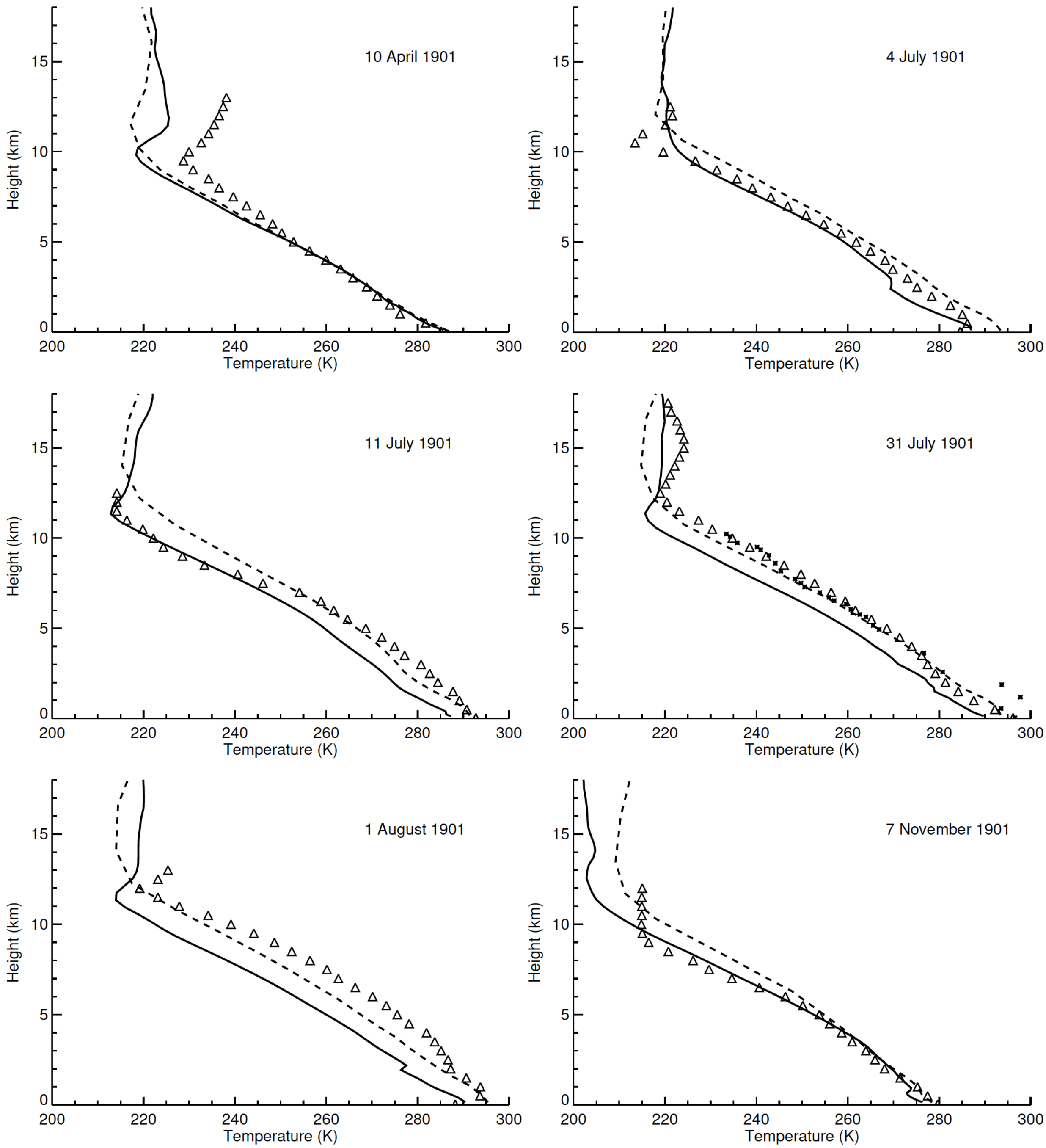


FIG. 1. Graphic depiction of Assmann's temperature data provided in Tables 1 and 2 (symbols), compared to temperature profiles from two 20th century reanalysis products (taken at 12°E, 52°N and the nearest synoptic time): ERA-20C (full lines), NOAA-CIRES 20CR v2 (dashed lines). The crosses for the July 31 case mark the data taken by Berson and Süring during their manned balloon ascent that same day (data taken from report by Pelz in Beilagen zur Berliner Wetterkarte, 27 November 1998).