

Paraglider flight logs as hypsometers: daily temperature profiles of an Alpine valley, its diurnal heating, and the nearly level ceiling of thermals

Jörg Korner

Independent researcher, Switzerland

joergkorner@gmail.com

ORCID: <https://orcid.org/0009-0001-9201-7509>

Preprint statement

This manuscript is a non-peer reviewed preprint submitted to EarthArXiv.

The manuscript has been submitted for publication in the *Quarterly Journal of the Royal Meteorological Society*. Subsequent versions of this manuscript may have slightly different content. If accepted, the final version will be available via the “Peer-reviewed Publication DOI” link on this page.

Companion paper: J. Korner, Paragliders as probes of the Alpine boundary layer: sink polars from 86 000 flight logs and the flow field of a valley, EarthArXiv, <https://doi.org/10.31223/X5G23K>.

Licence

CC BY 4.0 (Creative Commons Attribution).

Data and code availability

The derived data (layer values of every flight with an anonymous flight key, daily profiles, thermals, the Payerne soundings as used) and the programs that produce them from IGC flight logs and every figure and number of the paper from them are archived at Zenodo, <https://doi.org/10.5281/zenodo.23418086>. The flight logs were provided by XContest and cannot be redistributed; no pilot is identified.

Paraglider flight logs as hypsometers: daily temperature profiles of an Alpine valley, its diurnal heating, and the nearly level ceiling of thermals

Jörg Korner

Independent researcher, Switzerland

joergkorner@gmail.com

16 October 2026

Abstract

A paraglider flight recorder writes a barometric and a GNSS altitude every second. Between two pressure levels, the difference in GNSS altitude is the thickness of the layer, set by its mean virtual temperature: each recorder is a hypsometer, and a fleet of them a sounding network over every flown slope. Applied to 31 677 logs from dedicated instruments in the Valais, Swiss Alps, the method yields a temperature profile between 1400 and 3900 m for 437 flying days of 2011–2026. Against the Payerne radiosonde the midday profiles agree between 2200 and 3600 m to a median of $+0.6$ K, with a spread of 1.0 – 1.8 K over 375 days. Climbing and sinking flight give the same profiles to 0.2 K; instrument families differ by ± 0.5 K in absolute level, not in differences within a day. Between 07–10 and 14–18 UTC the air over the valley warms by 4.0 K at 1940 m and 1.7 K at 3020 m, the same within one 10-km cell as over the whole valley, against a few tenths of a kelvin in the free atmosphere, storing 2.5 MJ m^{-2} between 800 and 700 hPa. The ceiling of thermal lift, the upper envelope of the observed climbs in cells of 2.5–10 km, rises only 210–320 m for 1000 m of terrain (factors 0.21–0.32), the hour of day accounting for less than 0.1. Thin warm layers along slopes do not change the weight of the column and are invisible; the profiles therefore do not depend on where pilots fly.

Keywords: convective boundary layer; mountain meteorology; hypsometric equation; crowd-sourced observations; thermals; Alps

1 Introduction

Every day with thermals, hundreds of paragliders fly for hours through the convective boundary layer of the Alps, and their flight logs, uploaded to online contests, are a record of that layer at a density no observing network provides: along every slope and over every valley that is flown, on every convective day of the year, for two decades. A companion paper (Korner, 2026b) read the vertical motion of the air from these logs, after deriving the sink polars of the gliders from the logs themselves. This paper reads their temperature, with a method that needs nothing beyond what the logs contain, tests it against a radiosonde on hundreds of days, and uses it for two questions about the mountain boundary layer on which campaigns and models disagree.

The convective boundary layer over mountains is poorly observed. Radiosondes are launched from the plains, aircraft campaigns last weeks, and the few mountain studies that exist disagree on basic questions. De Wekker and Kossmann (2015), reviewing the concepts, describe a boundary-layer top that follows the terrain in the morning and may become level

in the afternoon when the valleys heat fast enough, and note that detailed observations of this structure are still limited; airborne lidar over the Alps found aerosol layers that did not follow the topography (Nyeki et al., 2000). How strongly the elevated terrain heats the atmosphere in place is a related question: a valley warms more than the plain for the same sunshine because it has less air to heat per unit of surface (Steinacker, 1984; Whiteman, 2000), and the heating drives the slope and valley winds and the export of valley air to the free troposphere (Henne et al., 2004; Schmidli, 2013). Numbers for these processes come from a handful of campaigns such as the Riviera project (Rotach et al., 2004), and from models.

The measurement rests on a property of the logs that needs no polar and no segmentation: most flight recorders write two altitudes, one from a barometer and one from a GNSS receiver. The two together measure the temperature of the air, layer by layer, by the hypsometric equation, in the same way that Stone and Kitchen (2015) and de Haan (2026) extract temperature and humidity from the altitude reports of airliners. A paraglider does this at $1\text{--}2\text{ m s}^{-1}$ of vertical speed, along slopes and over valleys, for hours, and on a good day hundreds of them do it at once.

The paper shows the method, its accuracy against a radiosonde and the checks that a flight is a usable hypsometer (Sections 2–4) and then uses the profiles and the thermals of the same logs for two questions: how much the valley atmosphere warms over the day, by height (Section 5), and whether the ceiling of the thermals follows the terrain (Section 6). Section 7 states what the method cannot see, and why that is also its strength.

2 Data and method

2.1 Flight logs

The data are the 86 369 IGC flight logs of the Valais, 2007–2026, provided by XContest (XContest, 2026) for research under a confidentiality agreement and described in the companion paper (Korner, 2026b); no log is redistributed and no pilot is identified. An IGC “B record” holds, once per second in most logs, the position, the pressure altitude and the GNSS altitude. The pressure altitude is, by the IGC specification (FAI International Gliding Commission, 2024), the measured pressure converted with the ICAO standard atmosphere referenced to 1013.25 hPa, whatever the pilot has set on the display. 66 606 logs (77%) carry two distinct altitudes; the others write one altitude into both fields. The instrument is named in the header. Logs from smartphone applications, and logs without an instrument name, are excluded from the temperature work for the reason given in Section 2.3; 31 677 logs from dedicated flight instruments remain (XC Tracer, AIR³, Flytec, Flymaster, Syride, Naviter, Skytraxx and others). Days with at least 20 such flights are used: 469 days, of which 437 from 2011 on, with 14 918 flights.

2.2 Layer temperature from two altitudes

The pressure altitude z_p is inverted exactly to the measured pressure, $p = 1013.25 (1 - 2.25577 \cdot 10^{-5} z_p)^{5.25588}$ hPa, so that the standard atmosphere drops out of everything that follows. The hypsometric equation gives the mean virtual temperature of a layer from its geometric thickness between two pressure levels,

$$\bar{T}_v = -\frac{g}{R_d} \frac{dz}{d \ln p}, \quad (1)$$

where z is the GNSS altitude, $g = 9.807\text{ m s}^{-2}$ and $R_d = 287.05\text{ J kg}^{-1}\text{ K}^{-1}$. Along each flight, within each 25-hPa layer between 875 and 525 hPa and within each of three windows of the day (07–10, 10–14 and 14–18 UTC, i.e. 09–12, 12–16 and 16–20 local summer time), z is regressed

on $\ln p$ over all fixes of that flight in that layer, provided there are at least 40 fixes spanning at least 15 hPa. The slope gives one layer temperature per flight, layer and window, with the mean position of the fixes; the median flight has 426 fixes in a layer, about seven minutes.

Two things cancel in the slope and make the method work. A constant offset of the barometer, which differs from instrument to instrument by tens of metres, and a constant offset of the GNSS altitude (geoid model, antenna, receiver), a few metres, do not change how many metres the flight loses between two pressure levels. For the same reason the temperature cannot be taken from two pilots flying at different heights: the difference of their altitudes contains the difference of their offsets, which is unknown. Each flight is its own hypsometer, and the many flights are averaged afterwards. The price is that a flight must climb or sink through the layer; a thin slice of air has no measurable weight. A single layer value of one flight has quartiles of ± 2.7 K about the median of all flights in the same layer on the same day, because one metre of error in a 250-m thickness is already 1.2 K; the spread is 2.3 K (MAD) for the most precise instrument family and 5 K for the least precise, and it shrinks with the time the flight spends in the layer, from 7 K for 40–100 fixes to 3 K for more than 800, as a random altitude error should. The daily profile is the median over the flights of a day, window and layer, and its uncertainty is the median absolute deviation divided by the square root of the number of flights. Layers with fewer than ten flights are not used. On a busy day (26 May 2023, 267 flights) this gives 60–240 flights per layer and uncertainties of 0.2–0.5 K.

2.3 Instruments

Three instrument effects were found and handled.

Recalibration. Some instruments continuously adjust their barometric altitude to the GNSS altitude. Their layer temperatures reproduce the standard atmosphere whatever the real air. A flight whose layer temperatures lie within 1.5 K of the standard atmosphere in at least two layers is excluded: 5.7 % of all layer values from 2011 on.

Thermal lag of smartphones. For smartphone logs the difference between the two altitudes drifts during fast climbs. A model in which the barometer follows the air temperature with a time constant of 15 min and a sensitivity of -6 m K^{-1} of lag explains 83 % of their residual. Dedicated instruments show no such effect (sensitivity 0.2 m K^{-1}). Smartphone logs are therefore left out.

Early instruments. Profiles from 2008–2010, when the first generation of flight instruments dominated, lie 2–5 K below the radiosonde (medians -4.7 , -3.6 and -2.1 K); from 2011 on the difference is stable between $+0.2$ and $+1.5$ K in every year. All results use 2011–2026.

2.4 Thermals

For Section 6, climbs were identified in the same logs as contiguous circling (heading change of more than 60° within a centred 20-s window) of at least 120 s with at least 150 m of height gain, the vertical velocity of the air being the barometric vertical speed smoothed over 15 s plus a constant sink of the glider of 1.3 m s^{-1} . This is a simpler rule than the segmentation of the companion paper and is sufficient here, since only the top height of each climb is used. Between 10 and 16 UTC it finds 54 481 thermals on 401 days from 2011 on. Days on which the thermal tops pile up at one height (95th minus 70th percentile of the tops below 150 m: cloud base or an airspace limit) are excluded, 15 days, leaving 53 320 thermals on 386 days.

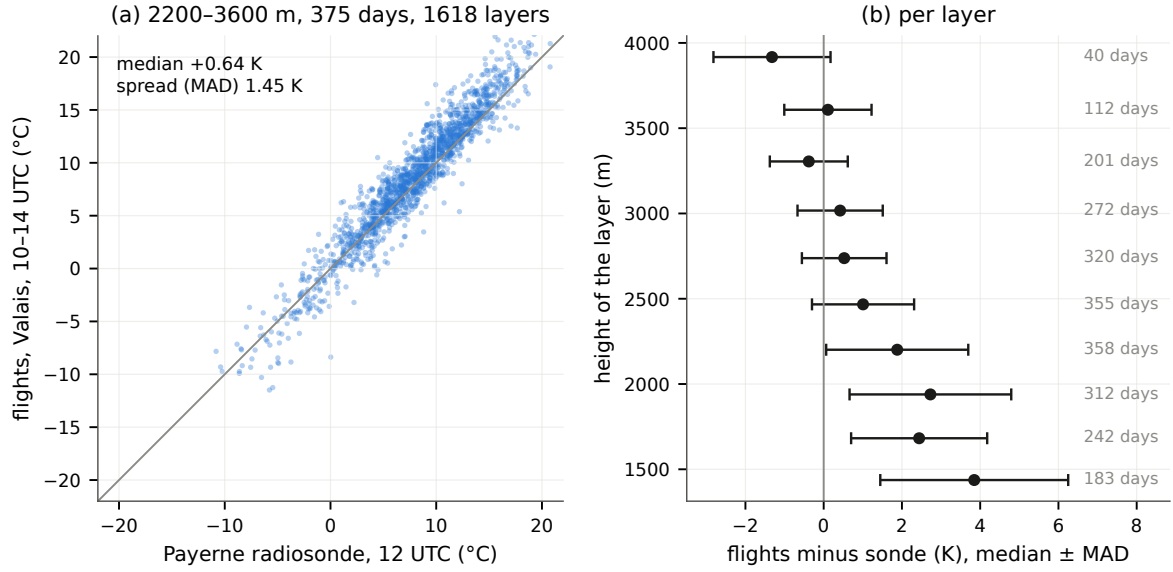


Figure 1: Layer temperatures from the flights against the Payerne radiosonde. (a) Virtual temperature of the layers between 2200 and 3600 m, flights of the Valais 10–14 UTC against the sounding 12 UTC, 375 days, 1618 layers. (b) Median and spread (MAD) of the difference per layer, with the number of days. Heights are those of the pressure levels on flying days (median of the soundings 2020–2026).

3 Validation against the Payerne radiosonde

Payerne (491 m, on the Swiss Plateau, 100 km from the centre of the Valais) launches a radiosonde at 00 and 12 UTC; the soundings are taken from the IGRA2 archive (Durre et al., 2018), with the virtual temperature computed from temperature and dew-point depression and averaged over the same 25-hPa layers. Figure 1 compares the 10–14 UTC profiles of the flights with the 12 UTC sounding on the 386 days from 2011 on that have both, 2406 layer comparisons.

In the layers centred between 2200 and 3600 m (800–650 hPa) the flight profiles lie +0.64 K above the sounding in the median, with a spread (MAD) of 1.45 K over 1618 layer comparisons on 375 days. Per layer the median difference is +1.9 K at 2200 m, +1.0 K at 2470 m, +0.5 K at 2740 m, +0.4 K at 3020 m, −0.4 K at 3300 m and +0.1 K at 3610 m, with spreads of 1.0–1.8 K. On 53 % of the days the mean difference over these layers is within ± 1 K, on 83 % within ± 2 K. Below 2200 m the Valais is increasingly warmer than Payerne: +2.4 to +2.7 K at 1680–1940 m and +3.9 K at 1440 m. This is not an error of the method but the heated valley atmosphere against a Plateau sounding that at these heights sits in its own boundary layer or above it; the comparison tests the method only where both sites are in the free or well-mixed atmosphere, and even there part of the spread is geographic, since Payerne is in a different air mass on some days. The decrease of the difference with height, from +1.9 K at 2200 m to zero at 3300–3600 m, is the heat excess of the valley fading out in the upper part of the mixed layer. Where exactly it reaches zero depends on the absolute level of the profiles, which carries an instrument offset of about ± 0.5 K (Section 4): with the two most precise instrument families alone the zero lies at 2600 m, with all instruments at 3300 m. The height of the top of the heat excess is therefore uncertain by several hundred metres, and no more is claimed for it than that it lies within the mixed layer.

4 Checks of the method

A flight does not cross a layer at one place and one instant. It moves 5–20 km horizontally while it climbs or sinks through 250 m, over several minutes, and a horizontal pressure gradient, a pressure tendency or a slow drift of either sensor during the crossing would enter the thickness as if it were temperature: one metre is 1.2 K. The bounds are small but not zero. The semidiurnal pressure tide has an amplitude of about 0.5 hPa at this latitude, so its tendency is at most 0.3 hPa h^{-1} ; over the seven minutes of a typical crossing that is 0.035 hPa, or 0.4 K, with opposite sign for a climbing and a sinking flight. A glide of 5 km across a synoptic gradient of 1 hPa per 100 km is 0.05 hPa, or 0.6 K, with a sign that depends on the direction of the glide. The following checks, all on the data from 2011 on, measure what is left of this in the profiles.

Climbing against sinking. Every layer value was computed a second and a third time from the climbing fixes only and from the sinking fixes only (barometric vertical speed, smoothed over 15 s, above $+0.3$ and below -0.3 m s^{-1} ; 74 470 and 100 724 values), and daily profiles were built from each. The profile from climbing flight is colder than the profile from sinking flight by $0.23 \pm 0.04 \text{ K}$ at midday and by $0.23 \pm 0.07 \text{ K}$ in the afternoon, and by $0.06 \pm 0.07 \text{ K}$ in the morning; per layer the midday difference is -0.3 to -0.5 K between 1940 and 2470 m and zero above 3000 m. The sign and the size are those of the pressure tide, which falls between noon and late afternoon and is near its maximum in the morning, and both halves validate against Payerne ($+0.47$ and $+0.84 \text{ K}$ in the core layers, against $+0.65 \text{ K}$ for all fixes). The warming of Section 5 comes out the same from either half: 3.7, 2.4, 2.3 and 2.1 K from climbing flight and 3.2, 2.7, 2.5 and 1.8 K from sinking flight at 2200, 2470, 2740 and 3020 m, against 3.4, 2.4, 2.2 and 1.7 K from all fixes.

Horizontal distance and time in the layer. Sorted by the horizontal distance the flight covers while inside the layer, from less than 1 km to more than 16 km, the layer values deviate from the median of their day and layer by $0.00 \pm 0.1 \text{ K}$ in every class; sorted by the time spent in the layer, likewise. Only the spread changes, as stated in Section 2. A horizontal pressure gradient does not leave a mean signal, because the glides go both ways.

Instruments. Relative to the median of all flights in the same layer on the same day, the instrument families read: XC Tracer -0.23 K , AIR³ -0.09 K , Flytec $+0.02 \text{ K}$, Syride $+0.21 \text{ K}$, Flymaster $+0.51 \text{ K}$ (errors 0.03–0.05 K; 12 000–34 000 values each), and Compass -2.2 K on 1.4 % of the values. Against Payerne, the profiles from XC Tracer and AIR³ alone lie -0.06 and $+0.18 \text{ K}$ from the sounding in the core layers, those from Flytec, Syride and Flymaster alone $+0.8$ to $+1.5 \text{ K}$; split into these two families, the daily profiles of the same layers differ by 1.1 K in the median. The absolute level of a profile therefore depends on the instrument mix of the day at the level of $\pm 0.5 \text{ K}$, and the $+0.6 \text{ K}$ of Section 3 is in part instrumental: with the XC Tracer and AIR³ family alone, the difference to Payerne crosses zero at 2600 m instead of 3300 m and is -0.5 to -0.6 K at 3020–3300 m. Differences within a day are not affected in the same way, since the mix changes little between the windows: the warming measured with Flytec instruments alone is 3.9, 1.8, 1.7 and 1.6 K at 2200–3020 m, within 0.6 K of the result from all instruments.

The exclusion rule. The rule of Section 2.3 that removes recalibrating instruments depends on the measured temperature itself. Without it the core-layer difference to Payerne is $+0.58 \text{ K}$ instead of $+0.65 \text{ K}$ with the same spread, and the warming changes by less than 0.2 K in every layer.

Independence. The uncertainty of a daily profile assumes that the flights err independently. Splitting the flights of each day, window and layer with at least 20 flights at random into two halves, the two half-profiles differ by 1.78 K (MAD, 1597 cases), against 1.89 K expected from the stated uncertainties: the random errors are independent. Splitting by instrument family instead gives the 1.1 K offset above, which is systematic. The stated uncertainties are therefore right for the random part, and the instrument offset is the systematic part, to be added when an absolute

temperature is wanted.

5 Diurnal heating of the valley atmosphere

Figure 2 shows the difference between the 14–18 UTC and the 07–10 UTC profile, layer by layer, as the median over the days from 2011 on that have both windows with at least ten flights in the layer (126 days at 2200 and 2470 m), and the corresponding 00-to-12 UTC difference of the Payerne sounding at the same pressure levels.

The air over the Valais warms by 4.0 K (quartiles over the days 2.8–5.6 K) at 1940 m, 3.5 K at 2200 m, 2.3 K at 2470 m, 2.1 K at 2740 m and 1.7 K at 3020 m between morning and afternoon. By midday three quarters of the warming is reached at 1940 m, two thirds at 2200 m, half at 2470 m and a quarter at 3020 m: the heating works its way up. The free atmosphere over the Plateau warms by 0.1–0.3 K at the same levels between 00 and 12 UTC, and by a further 0.3–0.6 K between 12 UTC and 00 UTC of the next day (0.62 K at 2200 m, 0.34 K at 3020 m, on the same days); the two soundings do not resolve the hours of the flight windows, but whatever part of this falls between 08:30 and 16 UTC, it is between a quarter and a tenth of the warming over the valley. The profiles are of virtual temperature; on the same days the specific humidity over Payerne falls by 0.1–0.5 g kg⁻¹ between 00 and 12 UTC at these levels and rises by at most 0.5 g kg⁻¹ on a quarter of the days, which changes the virtual warming by less than 0.1 K against the warming of the dry air. By season, July–August warms most at 2200 m (4.3 K, 75 days) and May–June more at 2470–3020 m (2.9 and 1.8 K, 35 days); the shoulder months March–April and September–October reach 2.9 K at 2200 m on 27 days.

The warming is a heat storage that can be stated per unit area without any assumption about density, since the mass of a 25-hPa layer is $\Delta p/g = 255 \text{ kg m}^{-2}$. The four layers between 800 and 700 hPa (about 2070–3160 m) warm by $3.46 + 2.31 + 2.13 + 1.67 = 9.6 \text{ K}$ in the median, which is $c_p \Delta p/g \sum \Delta T = 2.45 \text{ MJ m}^{-2}$ between the centres of the two windows, 7.5 h apart: 91 W m^{-2} averaged over the period, for this part of the column alone; the layer below it (825–800 hPa, 1940 m) adds 1.0 MJ m^{-2} or 38 W m^{-2} , measured on 37 days only. This is the heat that stays in the valley atmosphere; it is not the heat input. The surface sensible heat flux on Alpine slopes around midday is of the order of $100\text{--}300 \text{ W m}^{-2}$ (Rotach et al., 2004), and the difference between what the slopes supply and what the column stores is what the valley wind brings in as cooler air and what leaves through the top (Henne et al., 2004; Schmidli, 2013); neither is separated here. What the figure gives is the storage term of this budget, resolved in height and measured on 126 days.

The morning profiles are measured mainly near launches and along slopes, the afternoon profiles higher and over the valley. Because the method does not sense thin near-slope layers (Section 7), this does not bias the layer temperatures, but a horizontal difference on the scale of the valley would. The warming was therefore measured once more at the same place: in each 10-km cell with at least two flights in both windows, the afternoon value minus the morning value of the same cell and day. It is 3.7 K at 1940 m (103 cell-days on 95 days), 3.7 K at 2200 m (148 on 120), 2.2 K at 2470 m (79 on 71), 2.1 K at 2740 m (37 on 33) and 1.2 K at 3020 m (15 on 15), within 0.3 K of the valley-wide values except in the thinnest class; from the morning to midday in the same cell it is 2.3, 2.2, 0.8, 1.0 and 0.3 K against 3.1, 2.4, 1.1, 0.9 and 0.5 K valley-wide. The profile is an area mean over the flown region, not a column at one point, and the warming is the same where the same place is compared with itself.

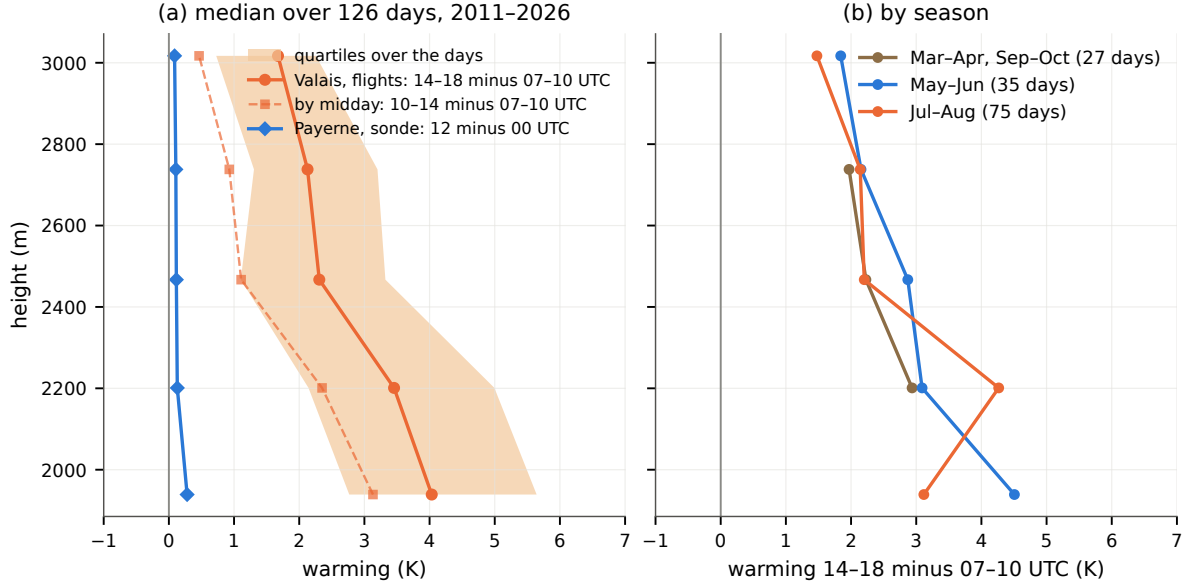


Figure 2: Warming of the valley atmosphere over the day. (a) Median over the days of the difference between the 14–18 and the 07–10 UTC profile over the Valais (circles, with the quartiles over the days as the band), the warming reached by midday (10–14 minus 07–10 UTC, squares), and the 00-to-12 UTC warming of the free atmosphere over Payerne at the same pressure levels (diamonds). (b) The same by season, with the number of days.

6 The ceiling of thermals and the terrain

6.1 Thermals are left early

Only 2.5 % of the thermals are flown out, that is, left with a climb rate below 1 m s^{-1} ; the median climb rate at the moment of leaving is 2.0 m s^{-1} . The height at which a thermal is left is therefore the pilot's decision, and the top of the lift is a lower bound. To see how much is missing, a remaining-climb function was learned from the flown-out thermals: each is cut artificially at the moment its climb rate first drops to 3.0, 2.5, 2.0 or 1.5 m s^{-1} , and the height it still gained after that is recorded by the trend of the climb over the previous 300 m and the strength of the thermal. Learned on the flown-out thermals of half of the days and tested on the other half, the function predicts the remaining climb with a median error of +25 m and a spread of 150 m. Of the 51 978 thermals left early, 18 680 gained less than 325 m, too little for the trend over the last 300 m, and keep their observed top; of the 33 298 others, 10 655 fall in classes whose learned remaining climb is zero (the climb was already fading), and 22 643 receive a remaining climb, 225 m in the median (quartiles 150–475 m). The function is learned from the 2.5 % of thermals that pilots flew out, which may differ from the rest; this is the reason for treating the correction as a check and the observed top as the quantity.

6.2 Does the ceiling follow the terrain?

What is measured is the upper envelope of the observed climbs, called the ceiling here for brevity; where it differs from the physical top of the mixed layer, it lies below it. For each day and each cell of a grid of 2.5, 5 or 10 km with at least eight thermals, the ceiling is the 90th percentile of the thermal top heights, and the terrain height of the cell is the mean of the SRTM 3'' elevation (Farr et al., 2007). Within each day with at least four such cells, ceiling and terrain are expressed as deviations from the day's mean, so that the overall level of the day cancels,

and the ceiling deviation is regressed on the terrain deviation over all days (Fig. 3). The 95 % intervals come from resampling the days. Within a day the terrain of the cells spans 750 m (2.5 km cells) to 1220 m (10 km) in the median, and the ceiling lies at 3230–3290 m.

The factor is 0.32 (95 % interval 0.23–0.42) at 2.5 km, 0.21 (0.15–0.28) at 5 km and 0.22 (0.17–0.25) at 10 km, from 925, 1399 and 1650 cell-days on 91, 143 and 184 days. A cell whose terrain lies 1000 m above the day's mean has a ceiling 210–320 m higher, not 1000 m. With the remaining climb of Section 6.1 added to every thermal left early, the factors are 0.23 (0.18–0.29) at 5 km and 0.21 (0.17–0.26) at 10 km, against 0.20 and 0.21 for the same cell-days without it: the pilots' leaving behaviour does not change the result. If it biases the factor at all, it is towards terrain-following, since a weak thermal over a valley floor is left earlier than a ridge thermal that is climbed out for the crossing.

The cells of a day are not all flown at the same hour, and the ceiling rises during the day, so the factor could contain a time-of-day effect. Within a day the ceiling rises by 77 m per hour (90th percentile of the tops per day and hour, 773 day-hours on 169 days; –170 m at 10 UTC, +200 m at 15 UTC relative to the day's mean), and the thermals over the lowest cells are flown 0.4–1.1 h later than those over the highest (12.3–12.5 h against 11.4–11.9 h). This gives the lowest cells a late-day bonus of 33–85 m, which lowers the apparent factor by at most 0.03–0.08; a correction for the hour should raise it slightly. Figure 3d shows the test. Taking cell-hours with at least eight thermals in the hour and at least four cells per day and hour, the factor from the deviations from the mean of the day and hour is 0.13 (0.08–0.19) at 5 km and 0.12 (0.07–0.17) at 10 km, from 473 and 518 cell-hours on 42 and 44 days; from the deviations from the day mean, on exactly the same cell-hours, it is 0.13 (0.08–0.20) and 0.10 (0.05–0.14). With two-hour windows (10–12, 12–14, 14–16 UTC) it is 0.15 (0.10–0.21) and 0.17 (0.14–0.21) from 842 and 1008 cell-windows on 95 and 114 days, against 0.13 (0.09–0.20) and 0.15 (0.10–0.19) on the same cell-windows from the day mean; within 10–12 UTC alone it is 0.16 (0.11–0.21) and 0.14 (0.09–0.19). Holding the hour fixed thus changes the factor by +0.00 to +0.02, the direction and size expected from the rise of the ceiling; the lower values of the hourly samples against the day-wide 0.21–0.22 come from the cells and days these samples select, the busy ones, not from the hour.

The upper envelope of the climbs over the Valais between 10 and 16 UTC is therefore nearly level, with a slight doming over high terrain, on all scales from 2.5 to 10 km: a factor of 0.2–0.3 across the day, 0.10–0.17 in the samples that allow the hour to be held fixed, and less than 0.1 of it from the hour. This is the afternoon state that De Wekker and Kossmann (2015) describe as reached when the valleys heat fast enough, and it is consistent with the lidar observations of Nyeki et al. (2000); here it is measured on 184 days. It fits the temperature profiles: by midday the valley atmosphere is mixed up to the ceiling, with lapse rates of 8.6–9.7 K km^{–1} in the layers from 1500 m below the ceiling to 400 m below it and 7.3–7.7 K km^{–1} in the last 400 m, and the heat excess of the valley over the Plateau fades out within the mixed layer (Section 3), so the top is set by the valley atmosphere as a whole rather than by the slope beneath. The thermal ceiling is one of the three observables that Hernández-Aguayo et al. (2026) relate to reanalysis predictors over France; the present result says what it is a ceiling of.

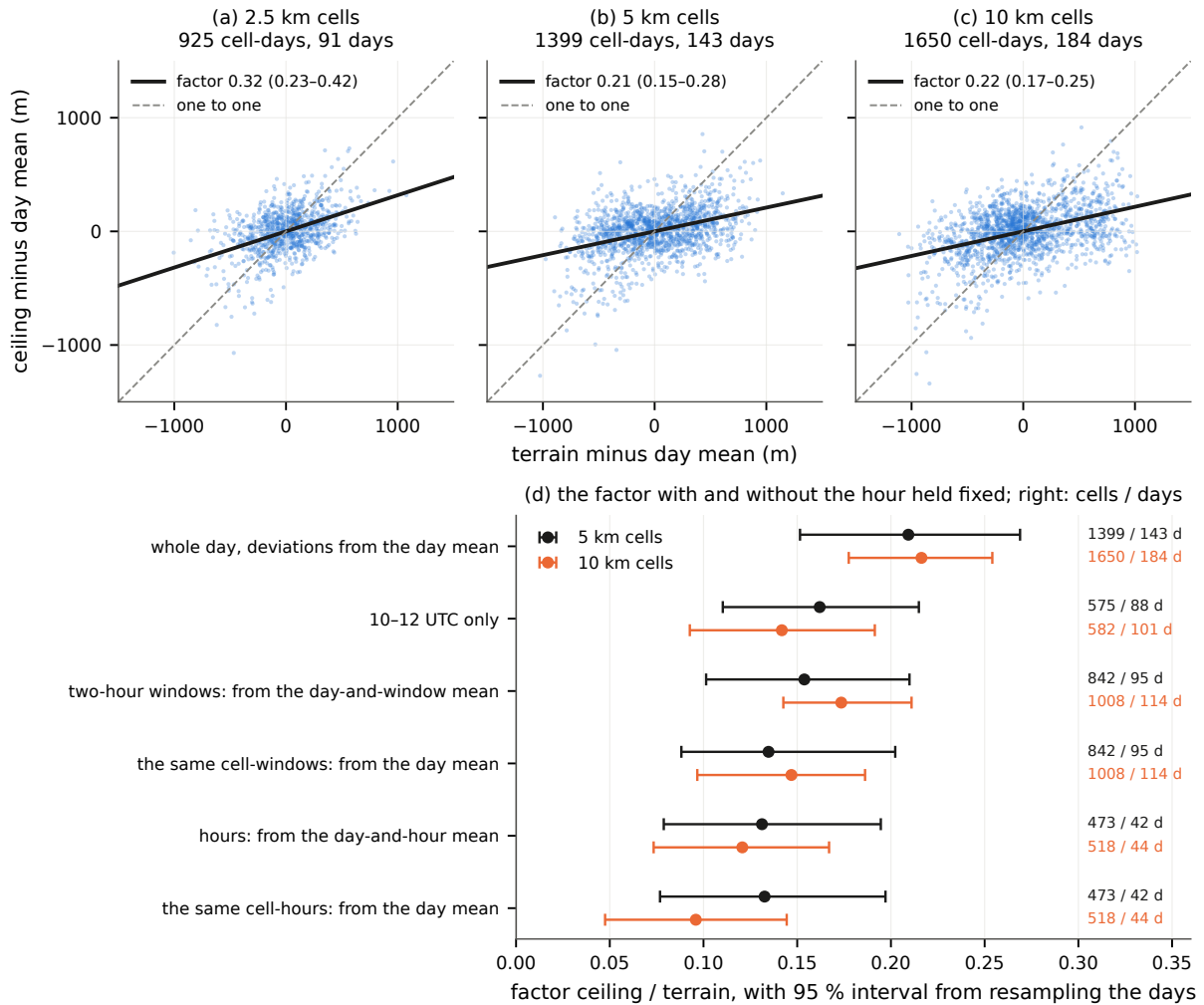


Figure 3: Ceiling of thermal lift against the terrain, within the same day. Each point is one cell on one day: the 90th percentile of the thermal tops in the cell, minus the day's mean over its cells, against the mean terrain height of the cell, minus the day's mean. (a)–(c) Cells of 2.5, 5 and 10 km. The line is the fit, with its factor and 95 % interval from resampling the days; the dashed line is a ceiling that follows the terrain one to one. (d) The factor for the whole day, for 10–12 UTC alone, and for the samples that allow the hour of the day to be held fixed: two-hour windows and single hours, each once with the deviations from the mean of the day and window or hour, and once, on exactly the same cells, from the mean of the day. Right: number of cell-days, cell-windows or cell-hours, and of days.

7 What the method does not see

Separating the 20 923 layer values measured within 300 m of the terrain at flight height from the 33 554 values measured in free air (more than 1500 m from terrain at flight height and 500 m above ground), the near-slope values are not warmer than the free air of the same day, window and layer: -0.3 to $+0.2$ K at midday and in the afternoon, with errors of 0.1 – 0.3 K, and between -0.7 and $+0.2$ K when split by the aspect of the slope. The slope layer, 50–200 m thick and 1–3 K warm (Whiteman, 2000), certainly exists; it does not change the weight of the column by more than a metre, and the pressure inside it is the pressure of the free air beside it, which is what drives the slope wind. The same holds for the warm core of a thermal. The hypsometer measures the temperature of the air as the pressure field sees it, averaged over everything that is horizontally connected. This is a limitation, and it is the reason why the profiles are insensitive to where pilots fly, and why the morning profiles along the slopes and the afternoon profiles over the valley can be subtracted from each other (Section 5).

For the same reason the method cannot see the stable air above the ceiling, which nobody flies through: on 291 days the highest layer of the midday profile lies 240 m below the ceiling of the thermals in the median, and on no day 250 m above it. How far thermals overshoot into the stable layer, and how the layer brakes them, therefore cannot be measured from these data, and the profiles end where the flights end.

8 Conclusions

A fleet of recreational flight recorders, never meant as meteorological instruments, yields daily temperature profiles of the boundary layer of an Alpine valley that agree with a radiosonde to half a degree in the mean and one to two degrees per day, over hundreds of days, at every flown slope between 1400 and 3900 m. The profiles show how strongly the mountain heats the atmosphere in place, an order of magnitude more than the free atmosphere warms at the same height in the same hours, with the storage term of the valley's heat budget resolved by height, the same at one place as over the whole valley; and the thermals of the same logs show that the upper envelope of the climbs over the valley follows the terrain only to a fifth or a third on scales of 2.5–10 km, with less than a tenth of that from the hour of the day: a nearly level lid in the upper part of the valley's heat excess. The absolute level of the profiles carries an instrument offset of about ± 0.5 K; the differences within a day, on which both results rest, do not. Both are quantities that numerical models parametrise and that have not been measured in this density. The blind spots are the thin warm layers along the slopes, which do not change the weight of the column, and the air above the ceiling, which pilots do not enter.

The companion paper used the logs as a measurement of the vertical motion of the air; this paper uses them as a measurement of its temperature. The two together, the flow field and the profiles, are the ingredients of a heat budget of the valley atmosphere that no campaign has had for more than a few weeks. Closing it needs the horizontal advection by the valley wind and the export through the top, which is the next step. Extending the method to the whole Alpine arc needs raw logs with both altitudes; segmented data with a single altitude do not suffice.

Data and code availability. The derived data and the code are archived at Zenodo (Korner, 2026a): the layer values of every flight (with an anonymous flight key and positions rounded to about 1 km), the daily profiles, the thermals, the Payerne soundings as used, and the programs that turn flight logs into these tables and these tables into every figure and number of the paper. The flight logs themselves cannot be redistributed under the agreement with their provider; the step from a log to its layer values can be reproduced with any IGC log from a dedicated flight

instrument that carries both altitudes, for example one downloaded from XContest.

Acknowledgements. XContest provided the flight logs. The Payerne soundings are from IGRA2 (NOAA NCEI), the terrain from SRTM.

Conflict of interest. The author declares no conflict of interest. The work received no funding.

References

- Siebre de Haan. Upper air humidity from automatic aircraft surveillance data. EGU sphere preprint egusphere-2026-717, 2026. URL <https://doi.org/10.5194/egusphere-2026-717>.
- Stephan F. J. De Wekker and Meinolf Kossmann. Convective boundary layer heights over mountainous terrain: a review of concepts. *Frontiers in Earth Science*, 3:77, 2015. doi: 10.3389/feart.2015.00077.
- Imke Durre, Xungang Yin, Russell S. Vose, Scott Applequist, and Jeff Arnfield. Enhancing the data coverage in the Integrated Global Radiosonde Archive. *Journal of Atmospheric and Oceanic Technology*, 35:1753–1770, 2018. doi: 10.1175/JTECH-D-17-0223.1.
- FAI International Gliding Commission. Technical specification for IGC-approved GNSS flight recorders. Fédération Aéronautique Internationale, 2024. URL <https://www.fai.org/igc-documents>.
- Tom G. Farr, Paul A. Rosen, Edward Caro, Robert Crippen, Riley Duren, Scott Hensley, Michael Kobrick, Mimi Paller, Ernesto Rodriguez, Ladislav Roth, David Seal, Scott Shaffer, Joanne Shimada, Jeffrey Umland, Marian Werner, Michael Oskin, Douglas Burbank, and Douglas Alsdorf. The Shuttle Radar Topography Mission. *Reviews of Geophysics*, 45:RG2004, 2007. doi: 10.1029/2005RG000183.
- Stephan Henne, Markus Furger, Stephan Nyeki, Martin Steinbacher, Bruno Neininger, Stephan F. J. De Wekker, Josef Dommen, Nicole Spichtinger, Andreas Stohl, and André S. H. Prévôt. Quantification of topographic venting of boundary layer air to the free troposphere. *Atmospheric Chemistry and Physics*, 4:497–509, 2004. doi: 10.5194/acp-4-497-2004.
- César Hernández-Aguayo, Matthieu Cristelli, and Michael Benzaquen. From flight logs to atmospheric science: Paragliders as convection sensors for identifying thermal predictors, 2026.
- Jörg Korner. Paraglider flight logs as hypsometers: derived data and code. Zenodo, 2026a. URL <https://doi.org/10.5281/zenodo.23418086>.
- Jörg Korner. Paragliders as probes of the Alpine boundary layer: sink polars from 86 000 flight logs and the flow field of a valley. EarthArXiv preprint, 2026b. URL <https://doi.org/10.31223/X5G23K>.
- Stephan Nyeki, Markus Kalberer, Ian Colbeck, Stephan De Wekker, Markus Furger, Heinz W. Gäggeler, Meinolf Kossmann, Matthias Lugauer, Douw Steyn, Ernest Weingartner, Martin Wirth, and Urs Baltensperger. Convective boundary layer evolution to 4 km asl over high-alpine terrain: airborne lidar observations in the Alps. *Geophysical Research Letters*, 27:689–692, 2000. doi: 10.1029/1999GL010928.

- Mathias W. Rotach, Pierluigi Calanca, Giovanni Graziani, Joachim Gurtz, Douw G. Steyn, Roland Vogt, Marco Andretta, Andreas Christen, Stanislaw Cieslik, Richard Connolly, Stephan F. J. De Wekker, Stefano Galmarini, Evgeny N. Kadygrov, Vladimir Kadygrov, Eugene Miller, Bruno Neininger, Magdalena Rucker, Eva van Gorsel, Heinz Weber, Alexandra Weiss, and Massimiliano Zappa. Turbulence structure and exchange processes in an Alpine valley: the Riviera project. *Bulletin of the American Meteorological Society*, 85:1367–1385, 2004. doi: 10.1175/BAMS-85-9-1367.
- Juerg Schmidli. Daytime heat transfer processes over mountainous terrain. *Journal of the Atmospheric Sciences*, 70:4041–4066, 2013. doi: 10.1175/JAS-D-13-083.1.
- Reinhold Steinacker. Area-height distribution of a valley and its relation to the valley wind. *Contributions to Atmospheric Physics*, 57:64–71, 1984.
- Edmund K. Stone and Mark Kitchen. Introducing an approach for extracting temperature from aircraft GNSS and pressure altitude reports in ADS-B messages. *Journal of Atmospheric and Oceanic Technology*, 32:736–743, 2015. doi: 10.1175/JTECH-D-14-00192.1.
- C. David Whiteman. *Mountain Meteorology: Fundamentals and Applications*. Oxford University Press, New York, 2000.
- XContest. XContest, 2026. URL <https://www.xcontest.org>. Accessed 2026-10-06.