

Use of Topographic Elevation Models to Identify Thermal Hotspots in Alpine Areas

Beda A. Sigrist
La Mulla 42
CH 1616 Attalens, Switzerland
bedasigrist@yahoo.de

Presented at the XXVIII OSTIV Congress, Eskilstuna, Sweden, 8-15 June 2006

Abstract

Thermals are part of the atmospheric energy flow caused by solar irradiation. The question behind this project, called TherMap, has been whether variations of the solar irradiance, caused by the local topography, could be a valid predictor of thermals under ideal meteorological conditions. Using digital elevation data the local irradiance, therefore, was computed for each cell, date and time, and the results displayed on maps, leading to first plausible results for the morning hours of mountain areas. In a second step these models were refined to consider the thermal inertia of the soil and the air, the different vegetation factors, as well as the reflection of snow surfaces. For Alpine areas the resulting maps turned out to show a high level of agreement with superimposed flight tracks. For topographically less differentiated regions, like the Jura, the results were mixed. No conclusive results could be obtained for topographically still smoother landscapes, where factors other than topographical ones are likely to be predominant.

Introduction

Intuitively the relationship between solar irradiation and thermals has been known by glider pilots for a long time. In order to study the solar irradiation in mountain regions, illuminating three-dimensional landscape models with flashlights has been a popular practice to identify locations with a higher potential for thermals. The method was obviously simple and had serious limitations in terms of precision and the assumed direct analogy between the observed illumination and the likely occurrence of thermals. I therefore believed that it was time to try a more precise approach and that an appropriate computer model, perhaps, could bring us further. I decided to build such a model, to find out how far this approach could lead us. Its name, TherMap, stands for thermal mapping.

I first simulated the above illumination effects on the computer. For this purpose I used a sufficiently detailed data base of the surface topography and a model of the position of the sun by calendar day and hour. Then I realized that mountain slopes well exposed to the sun work like solar panels, capable of absorbing large amounts of energy per horizontal cell below them, or per column of air vertically above them, which would eventually turn into thermals. Besides that I had to cater for the fact that the sunlight is attenuated by the atmosphere, depending on the visibility, the altitude of the surface and the solar elevation. With these two adjustments I could produce more sophisticated irradiance maps than any flashlight model would have permitted.

However, showing just an instant situation, these irradiance maps only seemed to indicate where thermals were likely to start in the morning. Towards the end of the afternoon, irradiation faded away with the solar elevation, far

ahead of the temperature and the known occurrence of thermals. I therefore needed a model expressing the thermal inertia of the surface and the air, and possibly even consider some secondary radiation effects, in order to approximate the resulting temperature increase in each location.

Finding such a model turned out to be the most difficult part of the project. I tested more and more complex models, but in parallel to this, also tried a simple mathematical smoothing algorithm, producing the resulting temperature as a kind of response to the irradiation input. I came to the conclusion that the latter model was not only much simpler and computationally efficient, but that it could also reproduce responses equivalent to those of physical models during the daylight hours of interest. Despite its better agreement with reality, I had to further refine this model by including the cooling effect of two types of vegetation, namely the forest areas and the seasonally variable vegetation periods. Finally I also had to consider the seasonal dependence of the altitude above which slopes below a critical angle reflect the sunlight (albedo).

When validated against actual flight-tracks, this model finally showed a good agreement between the mapped hotspots and the occurrence of uplifts during the flights in Alpine areas. Since the flight-tracks obviously tended to follow the upper edge of the hotspots, I also added an algorithm calculating the expected release points of thermals, starting with a model based on practical observations published years ago by Jochen von Kalckreuth.¹ These points turned out to be meaningful additions to the maps.

In the following paragraphs the steps outlined above are described in more detail, together with open issues and opportunities for further research and developments.

Irradiance maps

After some search and tests I finally selected the 90 meter SRTM digital elevation model (DEM), a free data base source describing the surface topography.² The 90 meter mesh width (actually 3 arc seconds) was almost ideal for the intended use, allowing an optimum balance between the level of detail needed and the data volume to be handled and stored. Since Europe lies further north, the longitude lines are about 30 percent closer than at the equator, which further allowed collapsing three cells into two. The models were then prepared for Switzerland, Austria and the French Alps. The limitations of the satellite radar scan, in terms of precision, and of reflection noise of water or ice covered surfaces, did not impair the work. It would of course have been desirable if the data available at that time would have been rectified for the lake surfaces. Due to those limitations, I could for instance go no further into modelling the cooling effect of water surfaces experienced by glider pilots.

For the position of the sun in terms of elevation and azimuth, I used a standard model, referring to local time, i.e. CET (Central European Time, UTC+1) for the centre of Europe, as this time definition is the highest solar elevation closest to noon.

To determine the primary irradiance, the scalar product of the solar direction vector and the normal vector of each mesh surface were computed, whereby the normal vector of the surface was based on a parabolic approximation in which the tangents determining the normal vector are parallel to the slopes of the lines connecting the adjacent elevation points in south-north and west-east direction (Fig. 1).

A more sophisticated method to determine the average normal vector, splitting the rectangular cells into two triangles folded along the steeper diagonal, to approximate erosion patterns, did not lead to significantly better results and was therefore abandoned.

For the Linke-turbidity⁷ of the atmosphere, describing the radiation energy scattered when passing the atmosphere, a value equivalent to a visibility of 12 kilometres has so far been used in all calculations. In practice this value is reported to be subject to considerable local and also some seasonal variations. The latter factor could possibly be included in future versions of the TherMap model. The introduction of the Linke-attenuation led to a decreased irradiation at lower altitudes and a generally reduced irradiance at low sun elevation angles.

The primary irradiance, corrected by the Linke-attenuation, refers to the irradiated surface, which usually is inclined. Since the inclined surface is larger than the horizontal cell surface underneath, the corrected primary irradiation has to be vertically projected on the underlying horizontal cell surface, which also defines the air column heated above it (Fig. 2). This leads to the equation:

$$I_h = I_s / \cos \alpha \quad (1)$$

whereby I_s = irradiance on sloped surface and
 I_h = irradiance projected on horizontal surface.

This slope induced adjustment had the most significant influence on the resulting irradiance maps, reflecting well the known amplifying effect of irradiated slopes on thermals in the mountains.

In order to consider the shadows cast by other mountains, the resulting shadow profiles had to be calculated for each hour, i.e. the profile below which the topographic surface is indirectly shaded. So far I have made no further calculations to estimate the cooling effect of the directly or indirectly shaded surfaces. However, since the irradiation deficit of these surfaces could be calculated, it should be possible to make further investigations on the dynamic effect of these colder areas on the local air flows.

Figure 6 shows an extract of a resulting irradiance map. The irradiated slopes can be well identified. Some of the whiter areas represent snow covered mountains. The white lines on the ridges are expected thermal release points explained in a later section.

Temperature increase maps

As already mentioned in the Introduction, the irradiance maps turned out to be good indicators of the locations where thermals are likely to emerge in the morning, both in the Alps and the Jura region. However, due to their direct dependence on solar irradiance, the results were equal for the same number of hours before or after the peak elevation of the sun. In practice daily peak temperatures (and thermals) are reached about two to three hours after the highest elevation of the sun, as for instance illustrated on p. 67 of Reference 4. A given temperature increase has basically the same thermal effect, independent of the absolute initial temperature. Therefore, I considered it sufficient for TherMap to just work with the temperature increase without dealing with the absolute temperature. For the sake of simplicity the term “temperature maps” has been used in the remaining text.

First, I tried a physical model with a single radiation absorbing body radiating off part of its energy as a function of its temperature. No matter how the parameters were set, the resulting temperature curves either reached the temperature peak too early and shortly, or were heating up too slowly in the morning. Some improvements could be achieved by a two tier model, in which a first tier, representing the surface, was heated up by radiation, exchanging some of its heat with a second body, the soil underneath. However, the added complexity was hardly worth the improvement.

A physical temperature model obviously required the consideration of *heterogeneous* surfaces with different thermal and radiation properties, which seemed to lead to a degree of complexity which I wanted to avoid in this project. Therefore, I reverted to what in engineering is called a black box approach, i.e. to determine the response function generating the most accurate temperature curve out of a given irradiance input, starting first with a simple mathematical smoothing model based on the formula

$$T_i = (1 - a)T_{i-1} + akI_i \quad (2)$$

where T_i = temperature at hour i , or $i-1$, respectively
 I_i = irradiance at hour i
 k = irradiance conversion factor
 a = smoothing coefficient

Figure 3 shows some of the resulting curves for different smoothing factors a . For these tests k was set equal to 1. The scale of the vertical axis is therefore not relevant.

The set of curves shows that for a smoothing factor of 0.25, the temperature peak is delayed by about two hours. However, when comparing this curve with reported values, it turned out to climb too slowly in the morning, and to decline slightly too fast after the peak temperature. From a mathematical viewpoint this could be corrected by making the smoothing factor dependent on the target time for which the temperature was calculated. This variation also made some physical sense, as it implied that the temperature during the later day hours depended more on the heat accumulated during the whole day rather than just the preceding hours. The target smoothing factor $a(h)$ leading to the best fit to measured values turned out to be sufficiently well described by the empirical equation

$$a(h) = 0.9^{(h-12)} b \quad (3)$$

whereby b = basic smoothing coefficient set equal to 0.2
 h = target hour

The formula led to the variable target smoothing factors shown on Fig. 4, and ultimately the temperature curve displayed in Fig. 5. The resulting temperature curve was now close to the shape of the measured temperature curve reported in Reference 3. The model has therefore been retained for the time being, with a view to further refinements, particularly a still closer correlation with the irradiance maps in the morning hours or a possible dependence on the altitude.

When comparing the initial temperature maps against practical experience, I realized that some other adjustments were needed first, starting with the effect of vegetation. By evaporating moisture, plants protect themselves against overheating by solar irradiation. The resulting cooling effect had to be approximated in the TherMap model, for two main factors, namely the forests and the seasonal grassland.

Concerning the *forests* I decided to characterize this effect by defining a general *Alpine forest belt* between the altitudes of 900 and 1500 meters above sea level, wherever the slope was steeper than 14 degrees, as slopes below this level tend to be used for pastures. The cooling effect was set to lead to a reduction of 25 percent of the basic temperature increase, gradually reduced to 12 percent towards the more arid south of France, where the vegetation is scarcer. On the temperature maps the transition zones above and below the forest limits have been deliberately blurred, to be closer to the real world. I think that these assumptions might be further refined, e.g. by also considering the azimuth and slope of the forests, since forests on very steep slopes tend to be less dense.

For the *seasonal effect of grassland* I determined the vegetation periods as a function of the altitude, on the basis of the mean monthly temperatures adjusted for the altitude and latitude.⁵ The mean monthly temperature allowing for active vegetation could be fixed at a value of 6^oC. The effect was set to be the same as for the forest belt (i.e. 25 percent declining to 12 percent towards the Mediterranean), and added to the latter one. The transition to the active vegetation surfaces was blurred once again, to be closer to reality.

To consider the effect of *snow surfaces* reflecting the sunlight (albedo), I further reduced the temperature increase by 40 percent for the surfaces laying above the mean monthly zero degree altitude and an inclination of up to 45 degrees, again blurred over an altitude of 500 metres.

With the present adjustments, the resulting temperature maps seemed to become plausible predictors for the occurrence of thermals in the Alps, even in the afternoon and evening hours. The steps taken for the validation of the maps are described in a separate paragraph.

Figure 7 shows a temperature map giving a first impression of the details identified by this method.

Thermal release spots

The Alpine distance flying pioneer Jochen von Kalckreuth¹ reported some 30 years ago that thermals basically tend to climb along slopes exceeding about 30 degrees until they reach a minor slope or an edge. With temperature maps already showing where thermals were expected to be produced, I became curious to find out where the corresponding release spots would be. Using a recursive algorithm, and a separate calculation plane, I let significant temperature increases of each mesh, determined by a minimum temperature limit, follow the steepest ascent according to von Kalckreuth's rule. As expected, most of the resulting release points did appear on the mountain ridges, but also at other edges known as thermal release spots or stretches. This seemed to confirm the basic validity of von Kalckreuth's rule. I therefore retained these spots as white dots on the irradiance as well as the temperature maps. Release spots appearing at the upper edge of well heated areas appeared to indicate particularly promising locations for uplifts. The white release points are well visible on Figs. 6 and 8.

Some of the temperature increases cumulated in release points that were very high and therefore lead to the question under what conditions thermals might spontaneously take off before reaching the edges defined by von Kalckreuth's rule. There is also a known aerodynamic effect which should, if possible, be included in future versions of the release model, namely the channelling of climbing airflows by ascending mountain groves. Such groves can prevent the thermals from following the line of steepest ascent. The evidence for this phenomenon is that significant thermals at the upper end of well irradiated mountain groves are very familiar to glider pilots. These examples indicate that there are interesting opportunities for further improving von Kalckreuth's rule.

Validating the maps

Comments by experienced pilots have certainly been most useful during a first phase, but basically insufficient for systematic validations. I therefore started to validate the maps by superimposing colour coded IGC flight logs to the corresponding maps. The colour codes were used to distinguish between ascending and descending flight phases. To avoid conflicts with other factors, such as cloud cover or strong winds, I used logs of long flights under ideal thermal conditions. The agreement with the temperature maps was already good, but still showed flight phases which did not seem to be affected by the higher temperature shown on the temperature maps. I realized that this tended to happen where the pilot had converted the lift into surplus speed. Hence the climb rate consumed by the surplus speed had to be added to the basic climb rate of the glider in order to arrive at the *net rate of climb* at any point of the flight, an interesting measure which would also seem to make sense in other flight analysis applications. Colour coding this net rate of climb on the flight tracks showed a high degree of agreement between the temperature maps and the flight logs and confirmed the validity of the maps for Alpine regions (Fig. 8). On some flights, and depending also on the altitude flown above ground, the effect of wind drift was sometimes visible. A *drift adjusted ground track* might therefore yield additional insights when analysing flight logs.

For the *topographically smoother* Jura region the flight log based validations led to a lower level of agreement between the temperature maps and the flight logs. On one hand the smoother surface is bound to result in less discriminating temperature differences. Another factor has been the fact that many of the flight logs found for this region revealed the existence of a lower cloud condensation level and hence the existence of clouds which may have covered the sun at locations supposed to be well irradiated in the temperature model. Overall I therefore concluded that the present temperature model was less reliable to predict the likely occurrence of thermals in regions like the Jura, whereas that the irradiance maps were also valid thermal predictors for the morning hours of such regions.

Despite these mixed results I also validated the model for the *even smoother regions* in the South of Germany. Apart from the only marginal topographical discrimination and the existence of a cloud base having the same effect as the one already mentioned for the Jura, the altitudes flown above ground were generally higher. The agreement between the temperature maps, showing the calculated temperature increase on the ground, and the flight logs turned out to be poor and of no real value. Neither did the evaluation of the irradiance maps lead to any better results. It seems that other models should be tried for these regions, for instance by using satellite infrared scans in addition to the topography.

Combining temperature maps and meteorology

In principle, the calculated temperature maps could be combined with current regional meteorological parameters, to ultimately obtain direct predictions for the likely occurrence of thermals. However, up to the temperature maps, the calculations have basically *been made independently for each cell of the digital map*, with the exception of the thermal release spots. When moving to a micro-meteorological model with the same cell size, complex interactions between the cells would have to be modelled, adding further dimensions leading to data volumes and a level of complexity beyond the possible value added by such a step, if feasible at all. I therefore concluded that it was better to stop at the level of the temperature maps.

In practice this means that the existing regional meteorological forecasts must remain the prime tool for distance flight planning. The temperature maps can play a complementary role, essentially for evaluating and planning alternative routes, and for posterior analyses of flight tracks, to find out where better opportunities might have existed. When using the temperature maps the user, therefore, must interpret the possible effect of meteorological factors like wind, cloud base, or the atmospheric stability.

Summary and conclusions

The project has shown that computer generated irradiance and temperature maps are a significant step forward from the traditional “flashlight” analogy, in terms of precision and practical insights. Such maps should also help to eliminate some of the crude and sometimes dangerous assumptions about thermal hotspots in the Alps. They can be a useful aid for pilots contemplating less known Alpine flight itineraries and their timing under good meteorological conditions. They are, however, unlikely to become a key tool in competitions, since the outcome of these is usually determined by the results obtained on meteorologically difficult days.

The project is however still young and open to further improvements, such as those mentioned earlier in this paper, namely

- The consideration of the cooling effect of lakes, ice-covered or predominantly shaded surfaces
- The average seasonal variation of the Linke-turbidity, depending on the geographical location
- The refinement of the heat accumulation model used for the temperature maps, e.g. its possible dependence on the altitude or the need to make the morning temperature maps more similar to the corresponding irradiance maps
- The dependence of the vegetation cooling effect on the slopes and azimuth of the surfaces concerned
- An extension of von Kalckreuth’s rule for determining expected thermal release spots in terms of the critical trigger heat or the channelling of thermals by mountain groves

- Use of wind drift adjusted ground tracks of flight logs for further validation of the maps
- Determination and, if possible, elimination of the causes for the still insufficient validity of temperature maps for the Jura area

For the Alpine countries, the morning irradiance maps and the temperature maps between 1100h and 1700h CET have been published on the Internet, for free downloading, hoping that the feedback by interested pilots will lead to further ideas and opportunities for improvement (Ref. 6). The intelligent use of these maps will hopefully contribute to make mountain gliding still more interesting and safer.

Despite the less conclusive results obtained for topographically smoother regions, other approaches should be tried. Unlike topographic radar scans, satellite infrared scans, probably the most promising data source, are not yet freely available. In addition such scans are dependent on time and season and would therefore imply bigger efforts to reach a coverage equivalent to the irradiance and temperature maps. However, the potential for further significant insights based on this approach seems to be promising.

Acknowledgments

The author thanks Dr. Olivier Liechti for his meteorological advice and general support, and the many pilots

who have encouraged him to pursue this project, particularly Christian Thomann, Ruedi Durrer, Philippe Progin, and Daniel Ramseier.

References

¹von Kalckreuth, J., "Erlebnis und Technik des Hochgebirgsfluges", 1st spec. ed., Motorbuch Verlag, Stuttgart, 2000, p.121, ISBN 3-613-02047-5

²Processed SRTM 90m Digital Elevation Data (DEM) for the Entire Globe, The CGIAR Consortium of Spatial Information /CGIAR-CSI), <http://srtm.csi.cgiar.org/>

³Solar Engineering Handbook Part 1, "Radiation Theory", ed. 2003, Meteororm, http://www.meteotest.ch/en/mn_dl?w=ber

⁴Solar Engineering Handbook Part 2, "Temperature Theory", ed. 2003, Meteororm, http://www.meteotest.ch/en/mn_dl?w=ber

⁵World Climate (climate data of specific locations), <http://www.worldclimate.com/>

⁶TherMap website: <http://www.aerodrome-gruyere.ch/thermap>

⁷Multimedia Space Educators' Handbook, NASA Johnson Space Center, Houston, Texas 77058.

<http://vesuvius.jsc.nasa.gov/er/seh/t.html#turbidity%20factor>; The European Commission Joint Research Center, PVGIS (Photovoltaic Geographical Information System)

<http://re.jrc.cec.eu.int/pvgis/solradframe.php?en&europe>

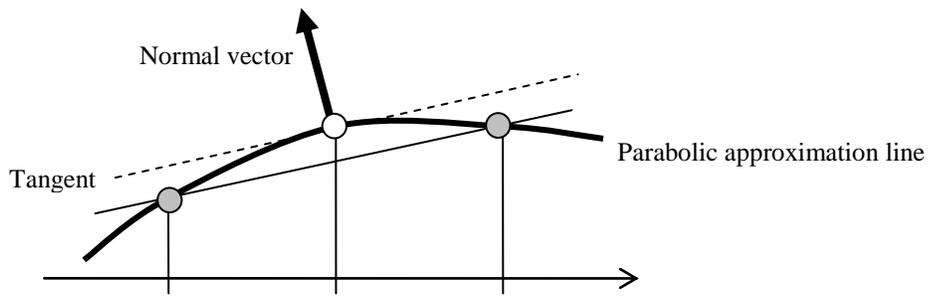


Figure 1 Parabolic approximation of tangent and normal vector

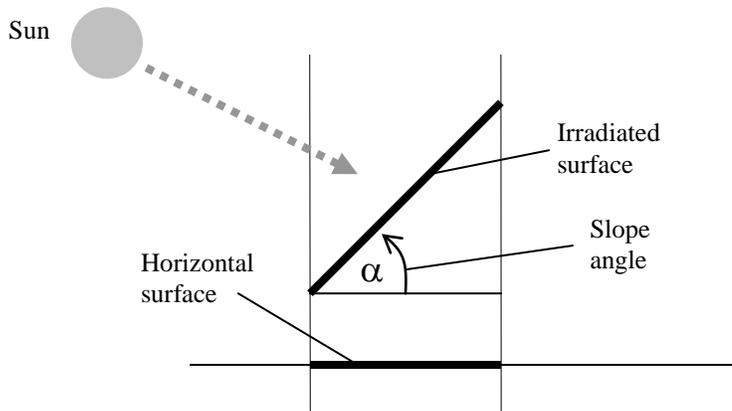


Figure 2 Relationship between irradiated and horizontal surface

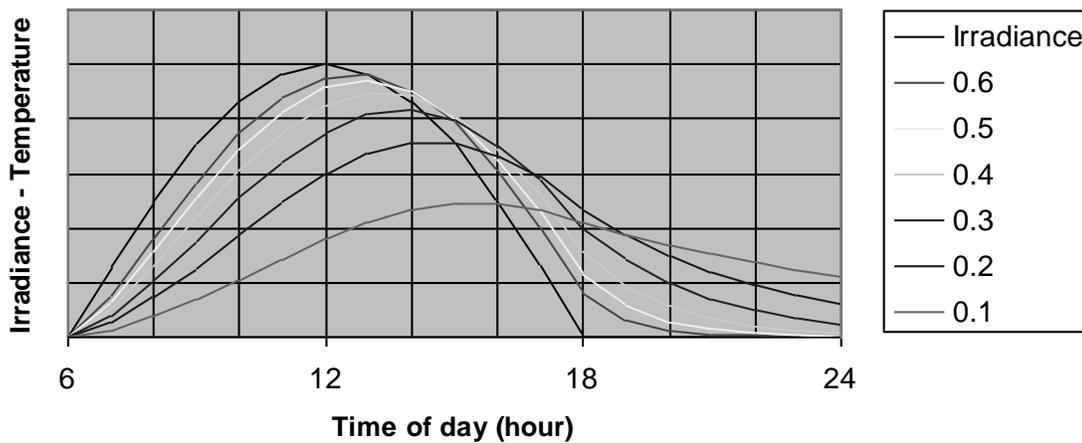


Figure 3 Time lag of temperature versus irradiance as a function of smoothing coefficient a

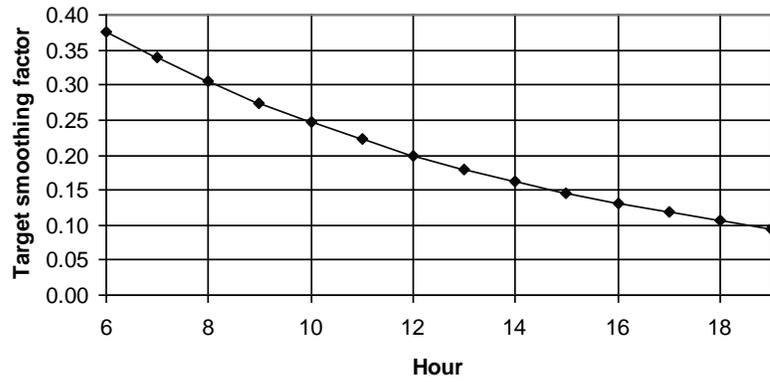


Figure 4 Target smoothing factors resulting from formula (3)

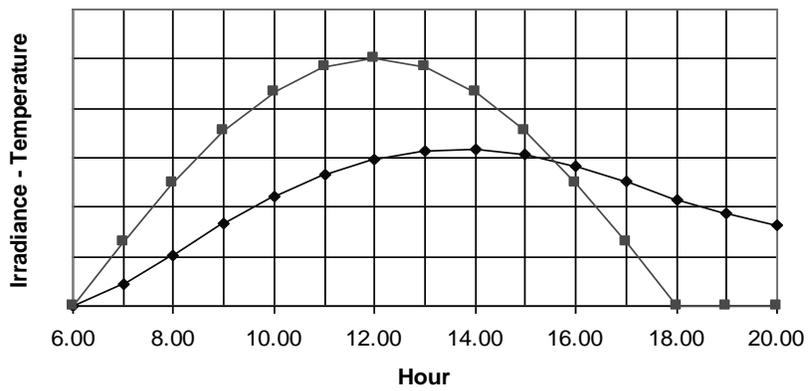


Figure 5 Temperature curve based on variable target smoothing factors

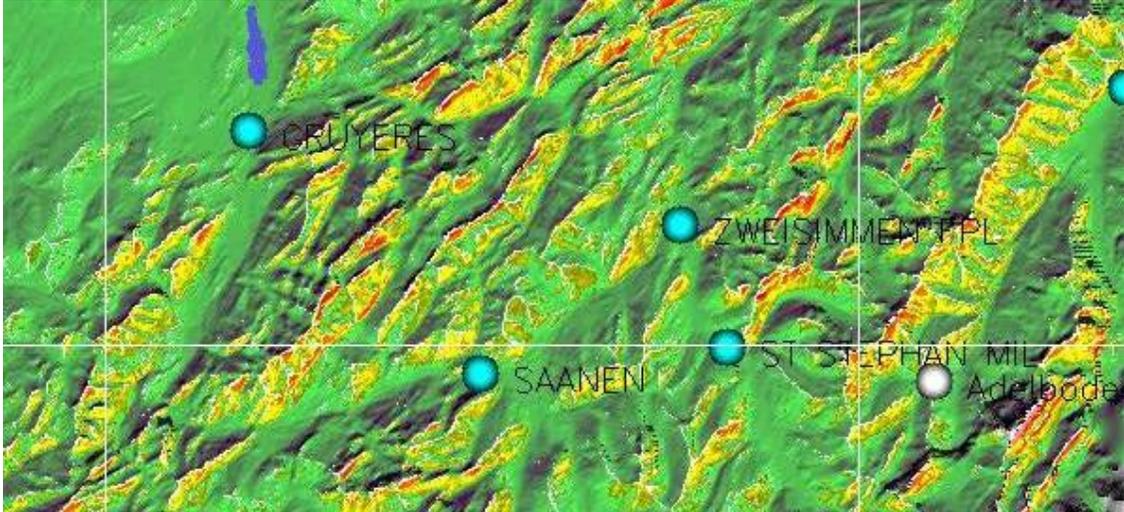


Figure 6 Extract of an irradiance map: Gruyère region/CH on Apr. 6 at 1100h MEZ. The hot (red) areas agree with the occurrence of morning thermals released at their white upper edges.

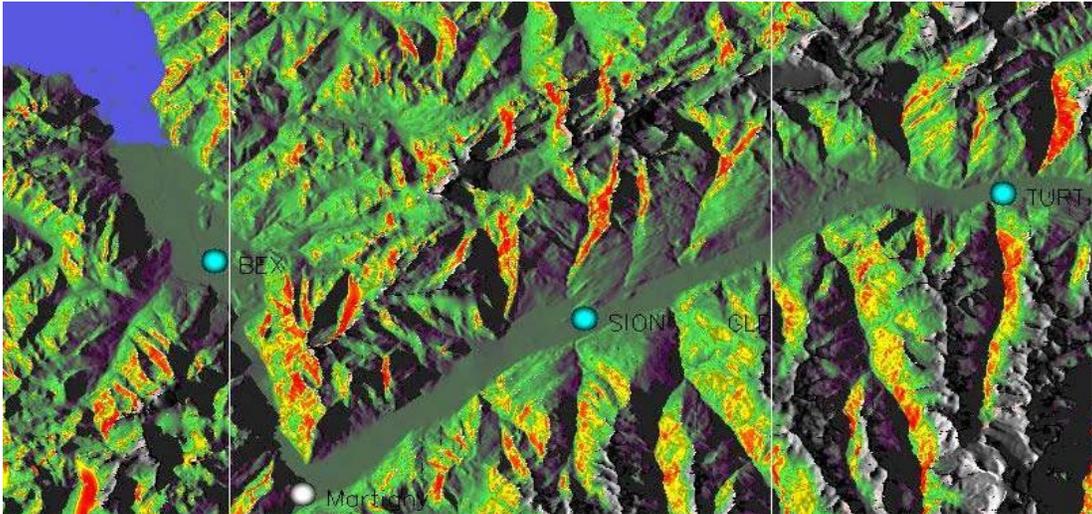


Figure 7 Extract of a temperature map: Valais/CH region on May 6 at 1700h MEZ. The upper ends of the hot areas are known for late afternoon thermals.

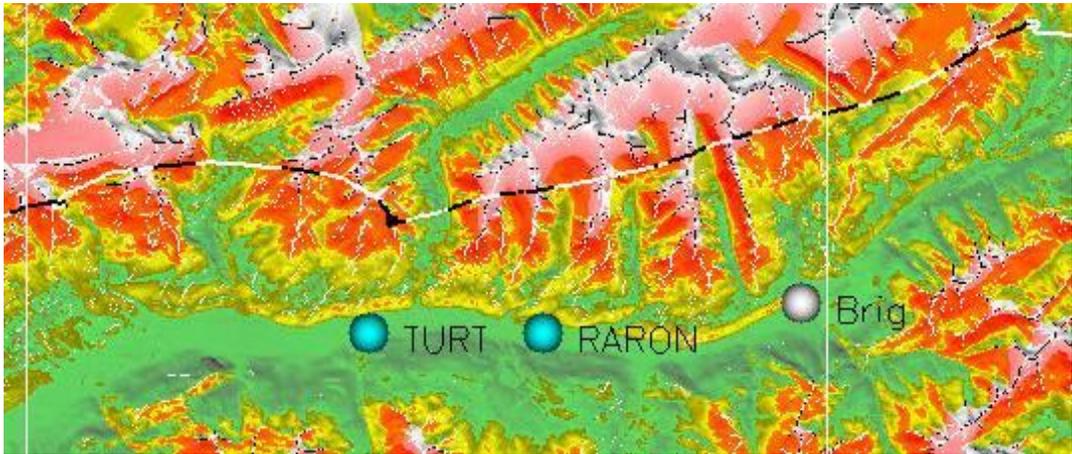


Figure 8 Validation of temperature map using a flight track of June 21, 1300h MEZ. The speed adjusted climbing phases are black, appearing typically at the upper end (release points) of the hot (red) surfaces.