

The Convective Boundary Layer

Jean Oberson, © February 2010

The convective boundary layer, hereinafter referred as CBL, sometimes called the atmospheric mixing layer or dry adiabatic layer is the lower tropospheric layer in contact with the ground heated by the sun and swept by the wind (Figure 1). It is therefore directly influenced by this surface, in particular thanks to convective phenomena (hence the term "convective") and dynamic one (wind) causing significant air mixing with horizontal and vertical turbulences (hence the term "mixing"). In other world it is the layer mixed by **dry** thermals or (vertical) wind shear. We usually only fly in the CBL. Therefore it is very important to us and usual weather flight handbook do not speak enough about it. In addition, CBL is a fundamental concept on which RASP bases. Convection is the scientific name for thermal.

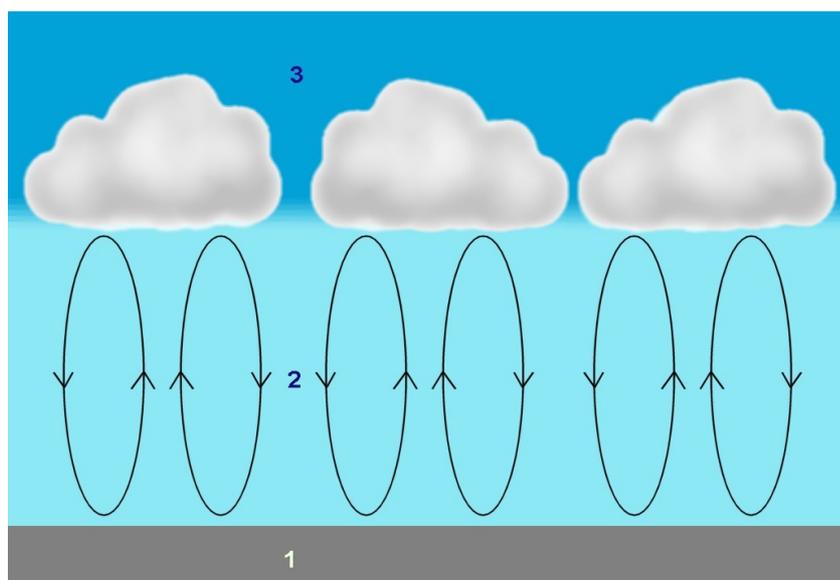


Figure 1 : The mixing convective boundary layer (2) above the ground (1) and below the upper troposphere (3).

When a vapour unsaturated air parcel rises (pressure decreases) or falls (pressure increases) in the atmosphere, e.g. between 2000m (approx. 800 hPa) and 3000 m (approx. 700 hPa), it expands or contracts respectively. This causes a decrease respectively an increase of temperature T of the parcel with a rate of $1^{\circ}\text{C}/100\text{m}$ (called adiabatic lapse rate). The humidity of the air measured in temperature dew point (Td) also decreases respectively increases, but with a smaller rate of $0.2^{\circ}\text{C}/100\text{m}$. Recall that Td is the temperature at which we must reduce the parcel of air for condensation to occur in liquid water. Td can be equal (saturated) or smaller than T but never

greater. At a given altitude, farther is T_d from T , drier the air is and vice versa. This difference $T - T_d$ is called “spread”. In the example of the figure 2, the air volume is large, cold and wet with $T = 5^\circ\text{C}$ and $T_d = 4^\circ\text{C}$ at 3000m and is small, warm and dry with $T = 15^\circ\text{C}$ and $T_d = 6^\circ\text{C}$ to 2000m. If air continues to rise slightly above 3,000 m, it becomes saturated with humidity ($T = T_d = \text{approx. } 3.7^\circ\text{C}$) and a small cloud, containing many very fine water droplets hanging in the air.

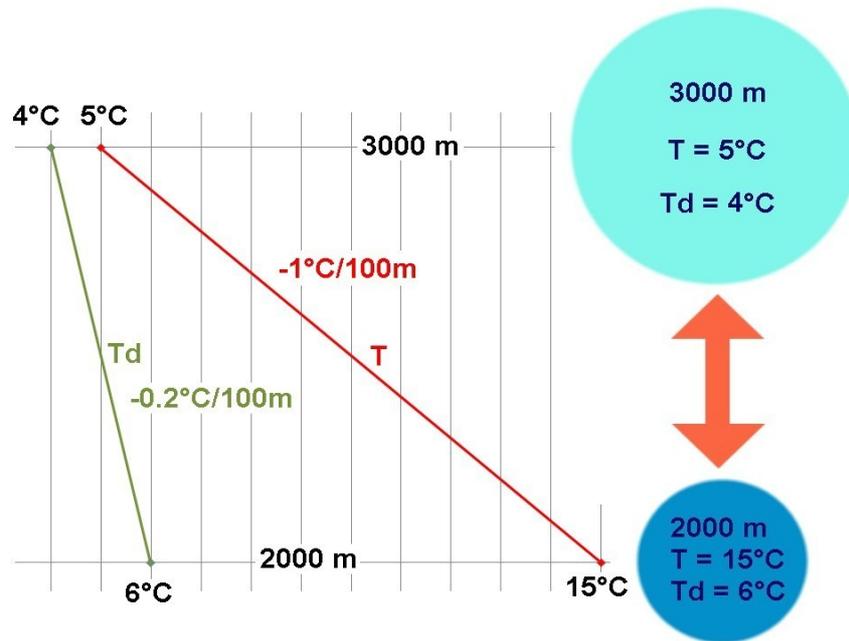


Figure 2: practical thermodynamics of a air parcel.

Some below described properties of the CBL follow from the principle described just above and from the continuous mixing of air in it:

1. The air in the CBL is usually more and less foggy with an upper limit usually visible when we are in altitude (Fig. 3). The haze comes from the mixing of air with dust and pollution from the ground.

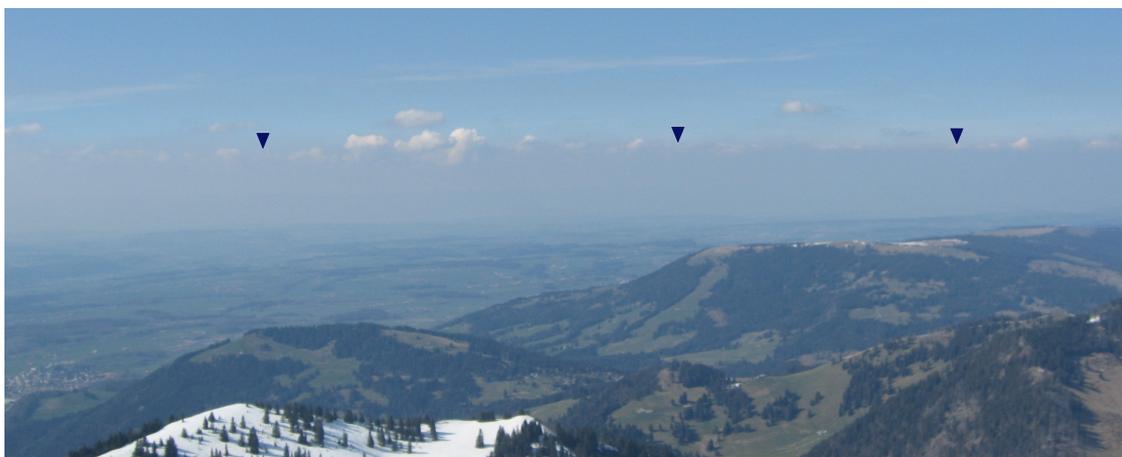


Figure 3: the hazy upper limit of the CBL, seen during a flight.

2. The lapse rates of T and Td in the CBL are near respectively 1° and $0.2^\circ \text{C}/100\text{m}$. This is evident, as the air ascends and descends constantly. In practice, close to the ground and on a depth of a few tens of meters, there is often a suradiabatic lapse rate, i.e. greater than $1^\circ\text{C}/100\text{m}$ during sunny days. This is the only occasion that we encounter in the suradiabatic lapse rate on a aerological diagram (Fig. 4).

3. The CBL thickness varies from few meters to several hundreds of meters depending from the general weather situation. If the air mass has a strong temperature contrast between the lower and upper troposphere, the CBL is more likely to be thick and vice versa.

4. In a relatively homogeneous topography, the CBL is itself homogeneous, i.e. its T and Td at the same altitude and its thickness vary very little from one place to another at a given time. On the ground, there are more T and Td contrasts. Winds are also often relatively homogeneous (similar) in speed and direction throughout the thickness of the CBL. In mountains the winds are more variable, with anabatic local breezes configurations adapting to the slopes and valleys.

5. The CBL evolves during the day. In the morning, it is not very thick. In the afternoon, after a strong solar heating, it reaches its maximum thickness (Fig. 5).

6. Usable dry thermal is only found in the CBL. Convections can sometimes continue above but only in large towering unusable cumulus.

7. There is often but not always a temperature inversion at the top of the CBL. Above the CBL temperature lapse rate is always below $1^\circ\text{C}/100\text{m}$.

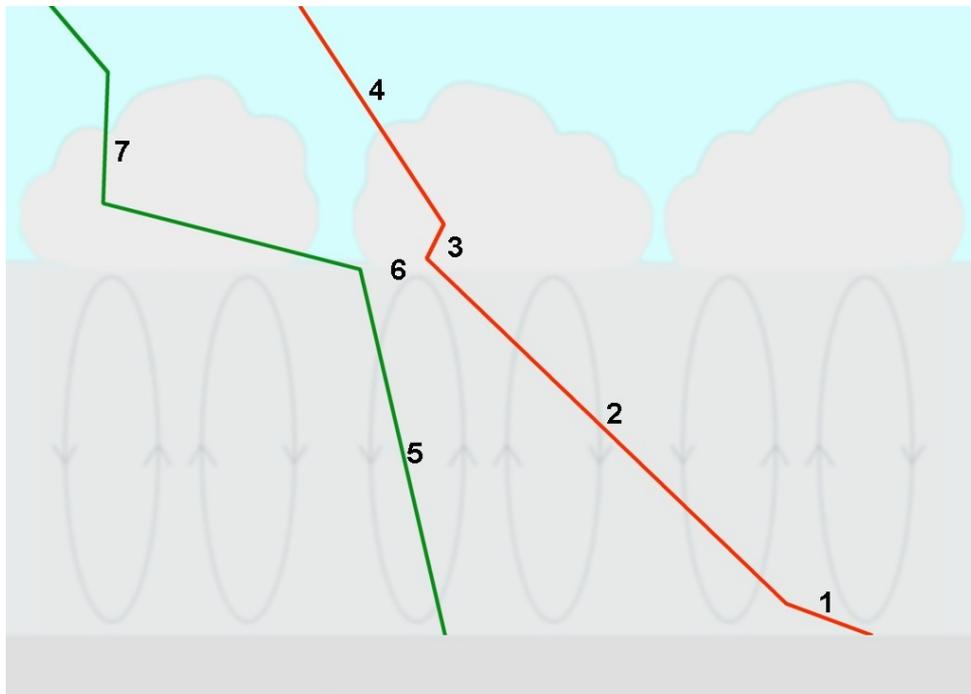


Figure 4: T-Td structure in the CBL. 1) Suradiabatic lapse rate. 2) Adiabatic lapse rate in the CBL. 3) T inversion. 4) Upper troposphere with T lapse rate less than adiabatic. 5) Td lapse rate in the CBL, $-0.2^\circ\text{C}/100\text{m}$. 6) T-Td difference (spread) is minimal at the top of the CBL. 7) Example of an upper tropospheric Td curve.

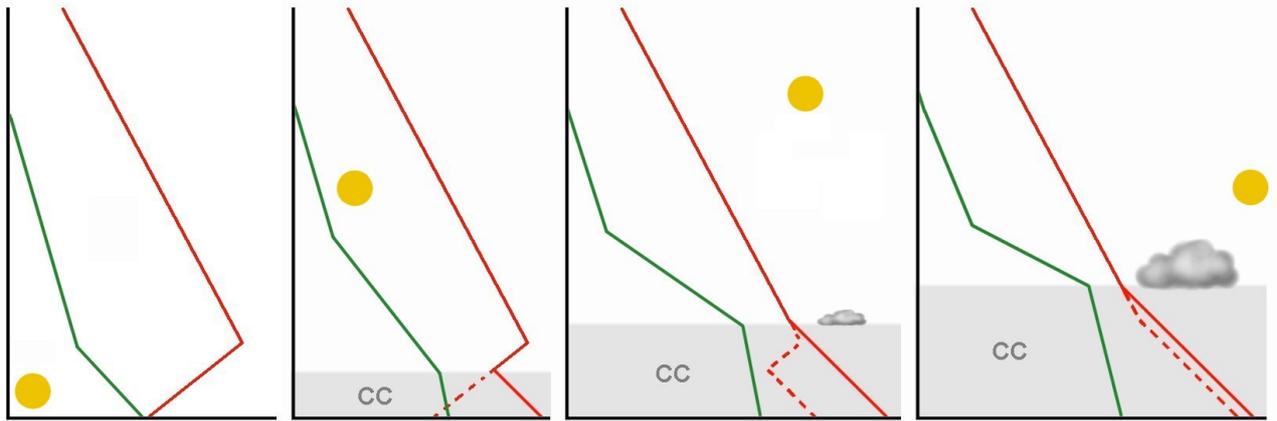


Figure 5: Evolution of the CBL (CC) during the day.

The thermal's buoyancy is due to its warmer air and at a much lesser extent to its wetter air than the ambient air. This can be evidenced by the equations of the gas law from which one can calculate the buoyancy of a air parcel from the T and Td differences between a thermal and its ambient air. Experiments with atmospheric measurements and numerical modelling experiments at microscale (large eddies simulation) have shown that differences between the air temperature and Td in thermals and in ambient air are not large, about 0.5 °C at mid height of the CBL (Fig. 6). On the ground the air temperature difference between the sources of convection and the surroundings are more pronounced. With the huge air volume of the thermal, these small differences nevertheless lead to several tons upthrust buoyancy.

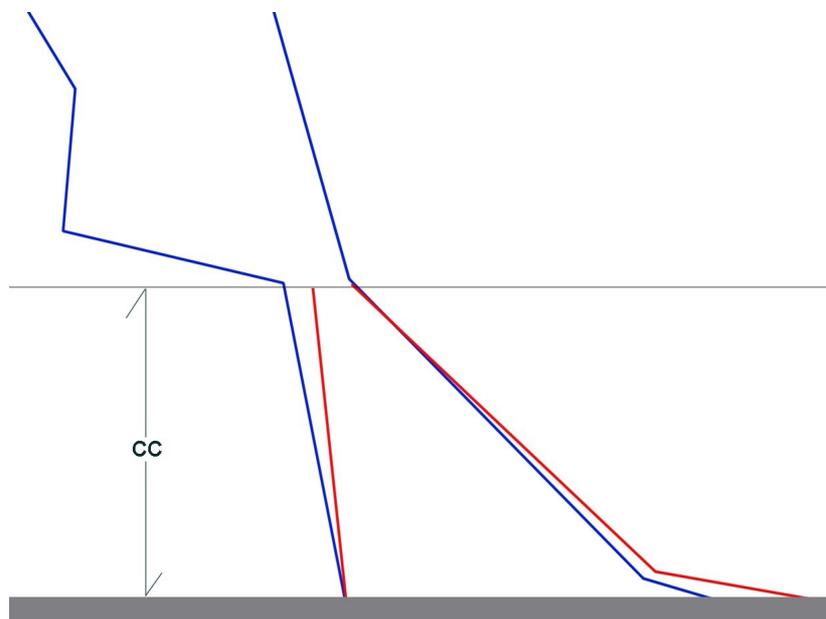


Figure 6 : Blue T and Td curves for the surrounding air. Red T and Td for the air inside the convections. That is a general tendency pattern.

For a favourable sky, i.e. with nice and high cumulus, appears the T-Td differences, called spread, should be 12-20 °C at the ground level and 2-4 °C at the top of the CBL. Still above the air should

be very dry. The curve pattern in Figure 4 is an ideal example. If the CBL is drier, i.e. the green curve (T_d) is even farther to the left from the red curve (T), thermals will be blue. If, however, the CBL is too wet, an horizontal overdevelopment of cumulus and stratocumulus is to fear. If the air is too moist above the CBL, one can expect vertical cumulus overdevelopment with thunderstorms or possible crossings of high clouds. If the CBL is not very thick, i.e. the top of the CBL is low, the thermals will be weak with small vertical extension.

In heterogeneous terrain, with mountains and lakes as in the Alps, the top of the CBL varies greatly (Fig. 7). On the ridges, the CBL is high and wet at the top, hence with many cumulus. Because the heating of the lowest air layers is less effective over large wet and relatively cold areas (marshes, lake) and due to subsidence of air above, the CBL there is relatively thin and appears very hazy, without cumulus and inert. In this case, CBL is called "blue hole" to mean that the region is not conducive to thermal soaring flight (figure 8).

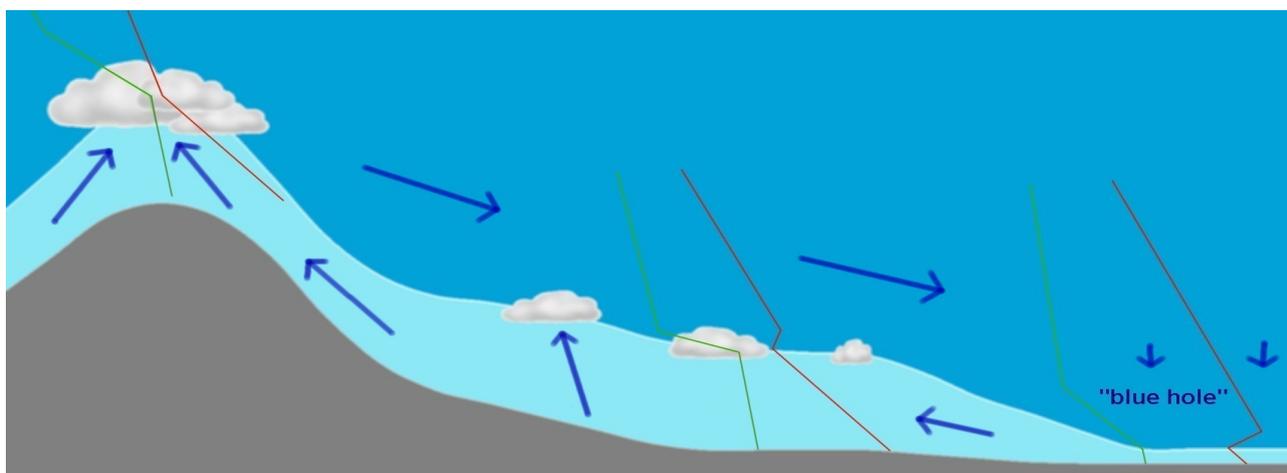


Figure 7: CBL variation according to the topography.

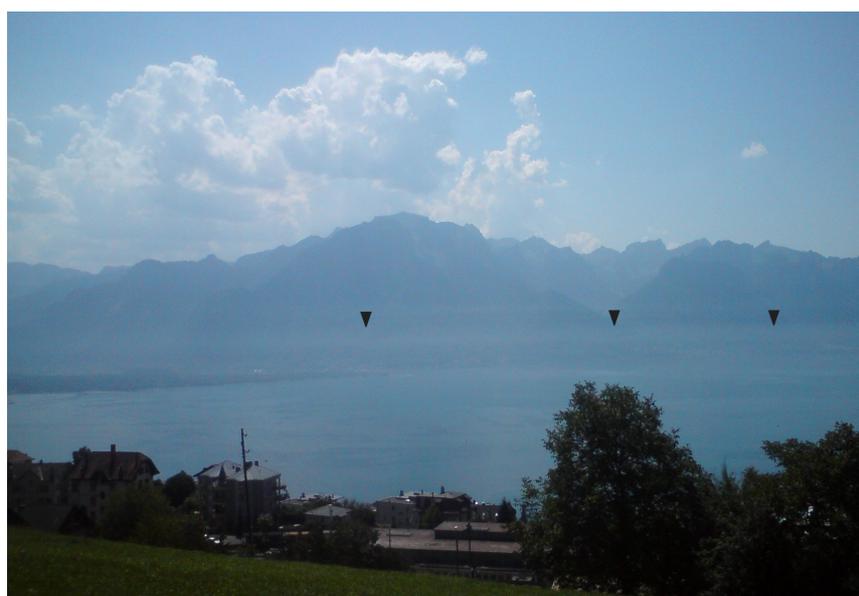


Figure 8 : The solid black arrows show the low top of the hazy CBL of the "blue hole" over a big alpine lake while imposing cumulus develop over the nearby ridges with thick CBL.

To look into these variations of the CBL, I examined a dozen of sunny days in the Valtellina and the Bergamo Alps (fig. 9) in the late spring and early summer 2009 thanks to a high resolution (2.2 Km) RASP version available on the website www.pedrini.info/gfs/. This small sample of soundings and charts from this RASP domain allow a proper average empirical evaluation of the CBL in an alpine region even if the model topography is simplified in comparison with the real topography

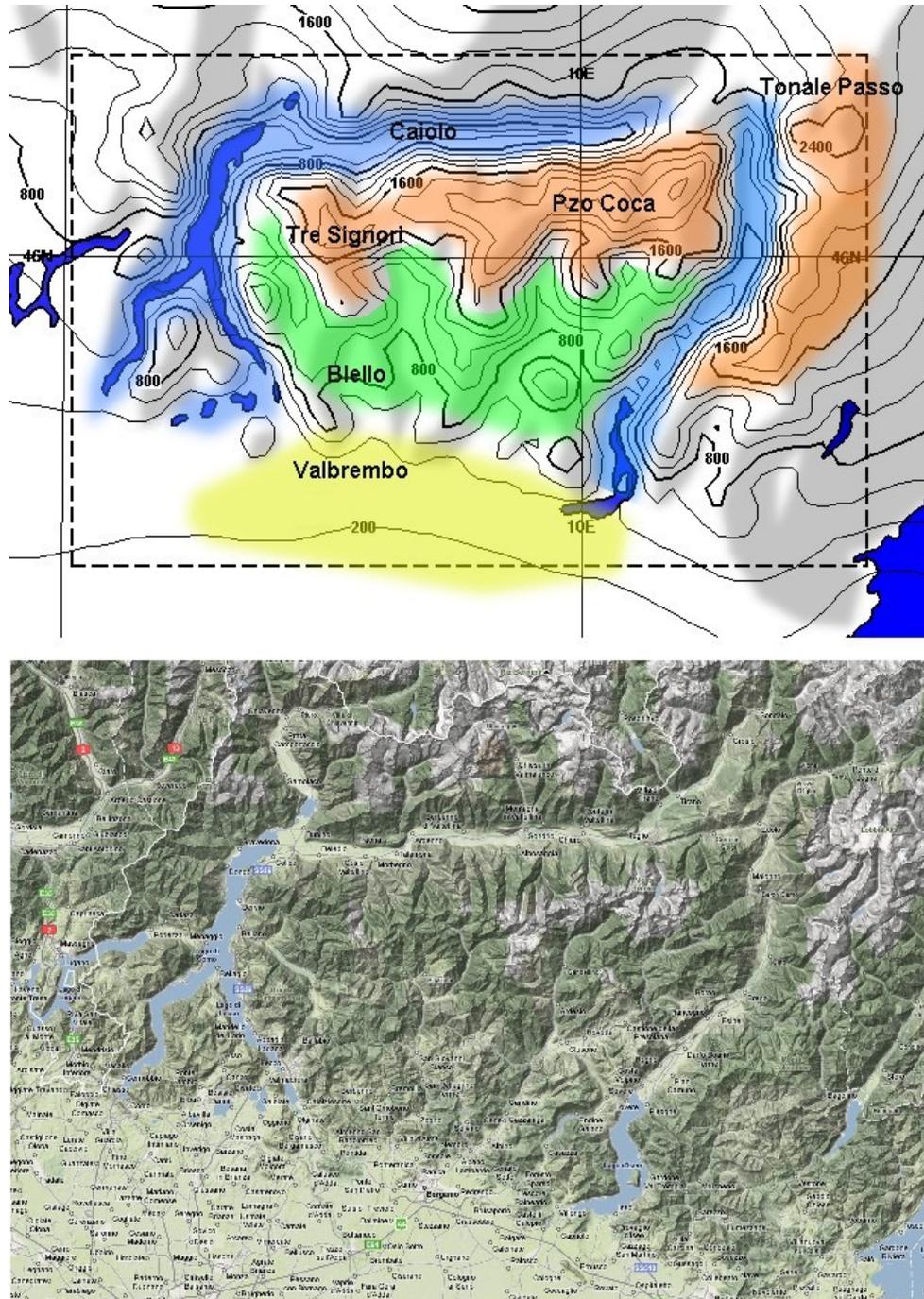


Figure 9: The simplified RASP model topography above and the more complex Google Map one of the Bergamo Alps area. Blue areas = « blue holes ». Red areas = ridge CBL. Green areas = foothills CBL. Yellow areas = flat land CBL. Valbrembo, Blello, Tre Signori, Caiolo, Pzo Coca and Tonale passo are selected location of computed soundings.

Compared to flat areas atmosphere adjoining the alpine peaks and valleys, the mountain's atmosphere presents at midday, some interesting features (figures 10 to 12) at the same height:

1. Air is warmer (2-5 °C) just above peaks and inside the valleys. This fact is known and reported by different authors. RASP confirmed. We can explain this by imagining that the air trapped in the valleys has a small volume to heat by the sun in comparison with flat open areas. The less polluted and less foggy atmosphere on the mountain's slopes which are anyway covered with less lush vegetation and more dry rocks and stones, can also contribute to greater warming of the air.
2. Conversely, around the top of the ridges CBL, cooling and humidification are clearly identifiable above the ridges. This phenomenon is favourable because it increases the thickness of the CBL upward. On the other hand, this humidification explains why there is often more cumulus on the ridges.
3. The CBL follows the terrain's topography. Thus its top is much higher on the ridges when it is not necessarily thicker than over the adjoining flat land. However, the thermal mountain have a greater vertical extent as it usually starts from the sunny slopes, located at a lower altitude below the tops of ridges (fig. 13). Moreover, the thermal is often reinforced by the suction effect of cumulus, more frequent in the mountains. For recall, the suction effect of a large cumulus cloud is due to the release of energy as heat during condensation, which causes an increase in temperature, and thus buoyancy, of the air in the cloud.

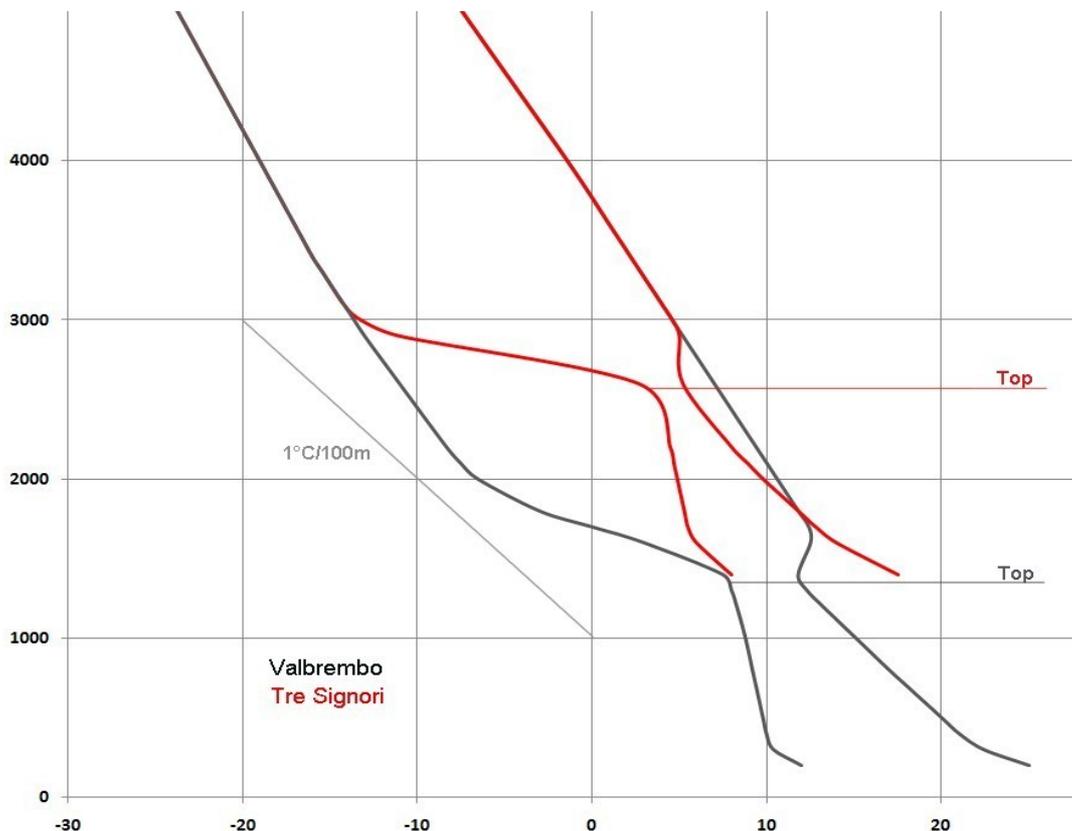


Figure 10 : comparison between the black profile of Valbrembo (flat land) and the red one of Tre Signori (adjacent mountain ridge).

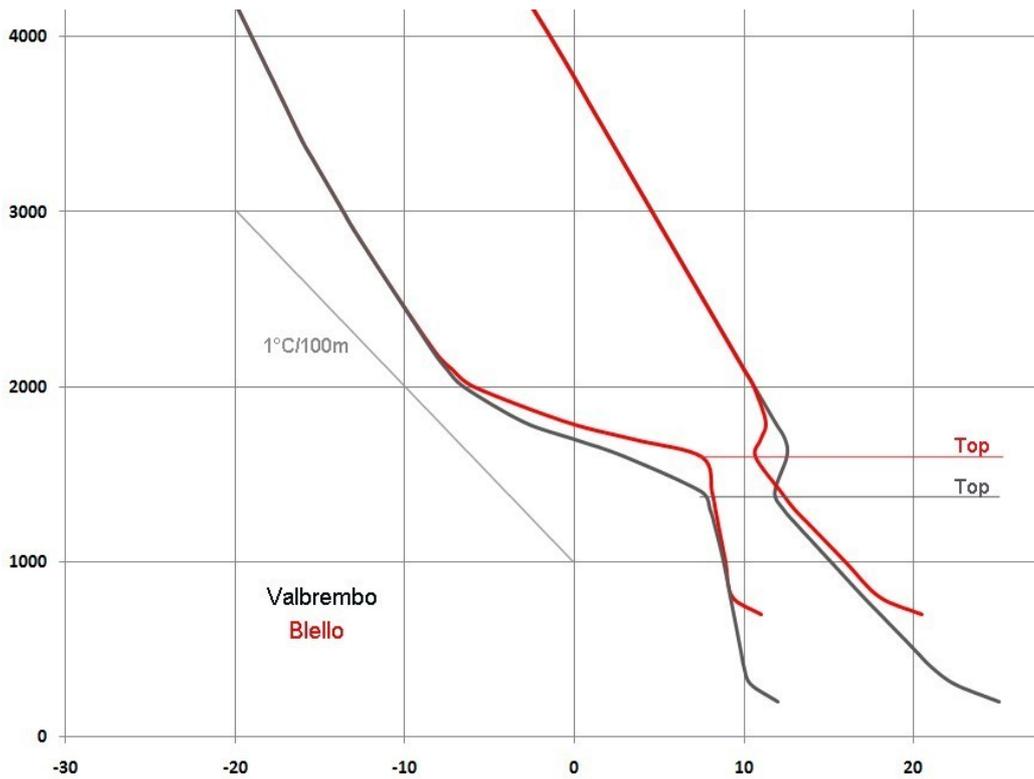


Figure 11 : comparison between the black profile of Valbrembo (flat land) and the red one of Blello (adjacent foothills).

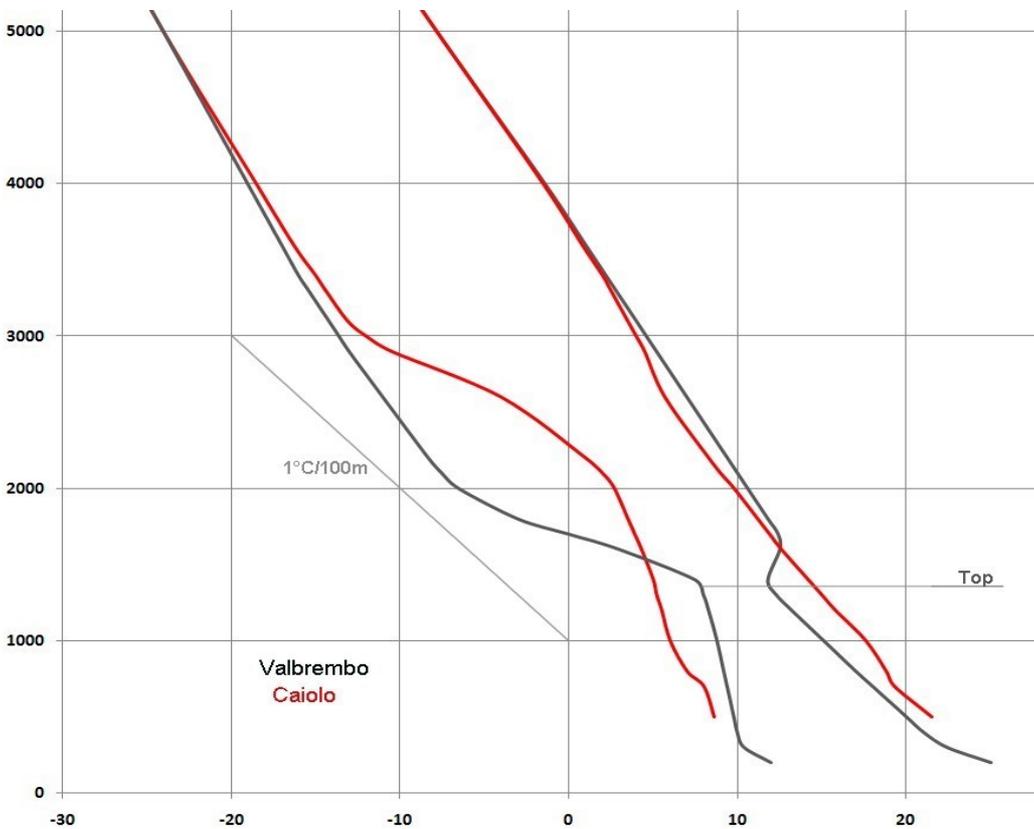


Figure 11 : comparison between the black profile of Valbrembo (flat land) and the red one of Caiolo (adjacent foothills).

(adjacent large and deep main valley).

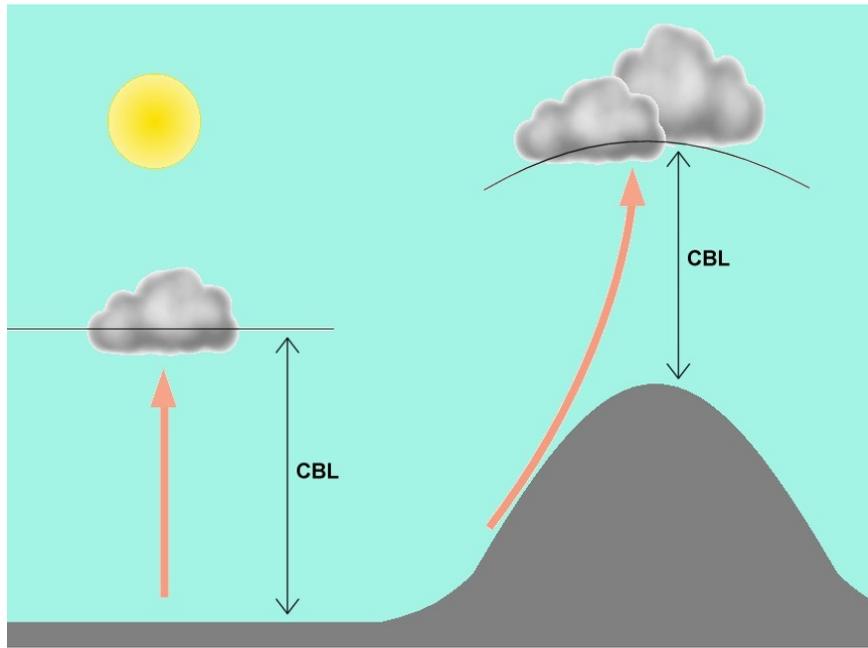


Figure 13 : In this example, CBL on the ridge is a little less thick than over the flat land but the vertical extent of the slope's thermal is larger than the thermal over the flat land.

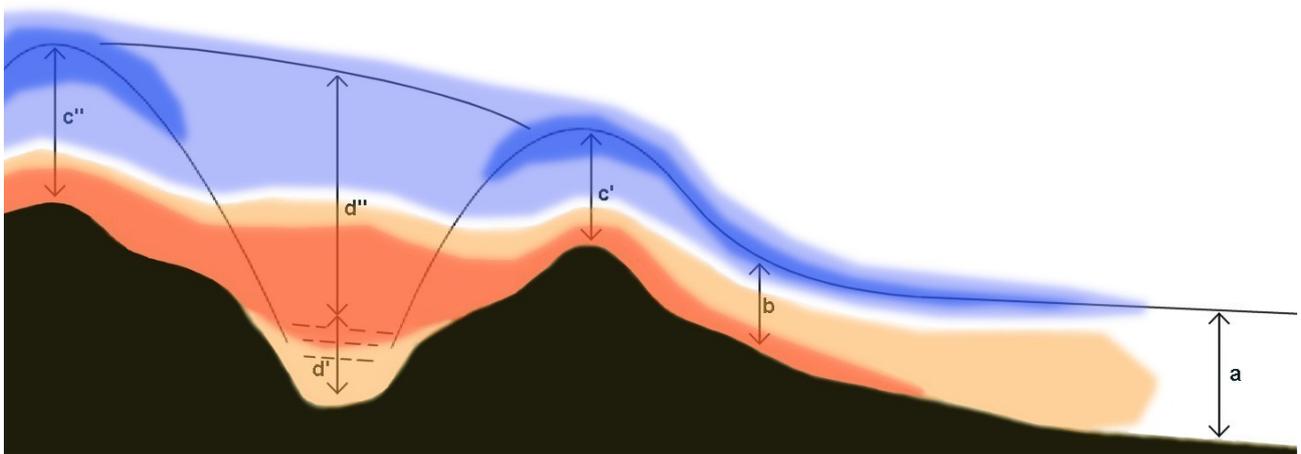


Figure 14 : N (left) -S (right) cross-section of the region. CBL in a: Valbrembo, in b: Bello in c' and c'': the main peaks (Tre Sgnori, Pizzo Coca, Passo Tonale). Note that Passo Tonale is actually a pass but, because of its narrowness, is not "seen" by RASP as such. CBL over Caiolo in d' (stable) and d'' (transition). Areas yellow-red = warmer air and blue areas = cooler and wetter air than the air above the adjacent plain (Valbrembo), at the same altitude.

The cross-section in figure 14 and the map of figure 9 summarize these features. We can observe that the CBL often seems somewhat crushed, and therefore less thick, over the foothills (segment b in fig. 14 and green area in Fig. 9) than over the main ridge. This could explain why thermals are

not always easy to negotiate on the lower slopes of a mountain whose peaks generate yet beautiful cumulus. At the bottom of the valley, the atmosphere is stable without significant CBL (segment d' in fig. 14 and blue areas in fig. 9). Above, I would name the atmosphere as a transitional layer that resembles a CBL (temperature gradient just below adiabatic lapse rate and dew point lapse rate slightly higher than $0.2\text{ }^{\circ}\text{C}/100\text{ m}$) as if the atmosphere above the ridges "rubs off" on the atmosphere in the valley (segment d", fig. 14) probably because of the mutually offsetting local breezes. The valleys, especially if they are large and contain a lake, are then typically "blue holes" (figure 8).

The CBL is formed more quickly in the morning on the ridge than on the plains. That is why the eastern faces are often conducive to an early thermal soaring flight. This can be explained by the fact that the nocturnal temperature inversion in the ground is less marked on the peaks than on the plain or the valley bottoms. Indeed, the cooled air during the night in contact with the ground falls rapidly from the peaks and high slopes to the plain or valley bottoms to accumulate. Thus weak nocturnal ground temperature inversion forms on the ridges and strong one over the lower ground surfaces. Weak inversion is obviously quickly to dissipate by the daytime heating than a strong inversion (Fig. 15).

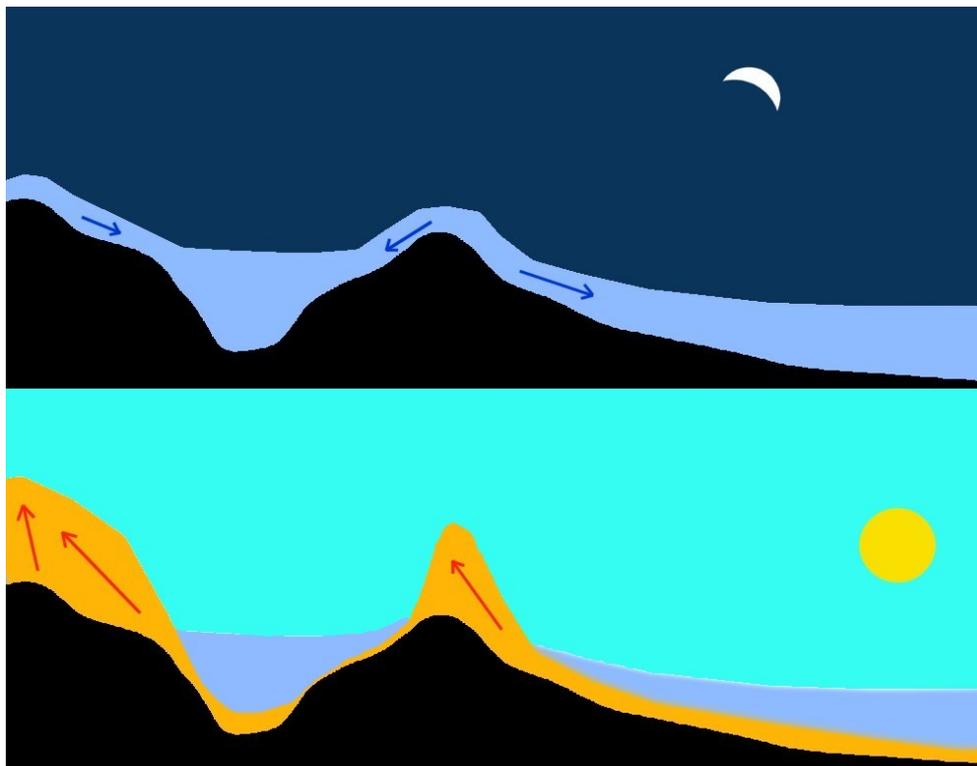


Figure 15 : Night ground temperature inversion in blue and early morning CBL in orange. Adapted from C. David Whiteman. Mountain meteorology. Oxford University Press, 2000.

Notes :

When vertical wind shear is strong (due to often strong wind varying with height), or convection weak, the BL top then results from small-scale mixing caused by wind shear rather than from usable

thermals. In such cases the "BL height" will not be reached, since small-scale eddies cannot support a glider so such a BL height has little relationship to the height that a glider will reach, though smoke released from the ground would be expected to eventually reach that height. In such cases the "Buoyancy/Shear Ratio" will be small.

The BL top height is also affected by vertical motion caused by convergence/divergence areas. In convergence respectively divergence areas, the BL top will be higher respectively lower.

In the presence of clouds the thermal top will increase above (i.e. outside) the BL, but the maximum thermalling height will then be limited by the cloud base.