Anabatic Winds

By R. S. Scorer, Imperial College, London

Prensented at the 10th OSTIV Congress, South Cerney, England, June 1965

Summary

Anabatic winds are upslope winds caused by solar heating of a slope. The mechanism and probable wind flow pattern, in the absence of large scale winds, are described. Observations on smoke and haze carried by such winds indicate that they are best developed when the air mass adjacent to the slope is stably stratified. The flow pattern is much more complicated than in katabatic winds caused by the cooling of a slope, but with the aid of a picture of the likely flow pattern anabatic winds could be more confidently explored for soaring purposes. However, more careful observations are needed because there are several factors at work whose relative importance can only be determined by experience: examples of these factors are angle of slope, nature of surface (rock, snow, trees, etc.), stratification of air mass, and large scale wind flow.

1. Upslope winds due to heating

An upslope wind is called anabatic when it is caused by the warming of the surface by sunshine. We are not concerned here with winds which blow up a slope because the mountain is immersed in a much larger airstream: an anabatic wind is a local wind. The corresponding downslope, or katabatic, wind is a much simpler phenomenon because only a shallow layer of air is cooled by proximity to the ground; but when the ground is warmed thermal convection rises as high as the static stability of the environment permits, and the depth of the warmed layer depends on factors which we shall now enumerate:

(i) *The rate of heat input into the air*. This is determined by the intensity of sunshine, the inclination of the slope to the incident rays, and the nature of the surface. Bare rock and ripe vegetation (e. g. brown grass) warm up rather quickly, whereas green vegetation remains cooler and converts the heat into latent heat as it transpires water vapour. A snow-covered surface, on the other hand, remains cool by reflecting the incident short wave (solar) radiation and emitting in long wavelengths.

(ii) *The static stability of the air mass*. If the stratification is neutral the thermals rise vertically from a heat source. But when the air mass is stably stratified the heating is confined to a rather thin layer and the surfaces of constant potential temperature are curled over to the surface, as indicated in fig. 1. Then the warm layer on the surface ascends the slope and the rest of the air mass sinks slightly.

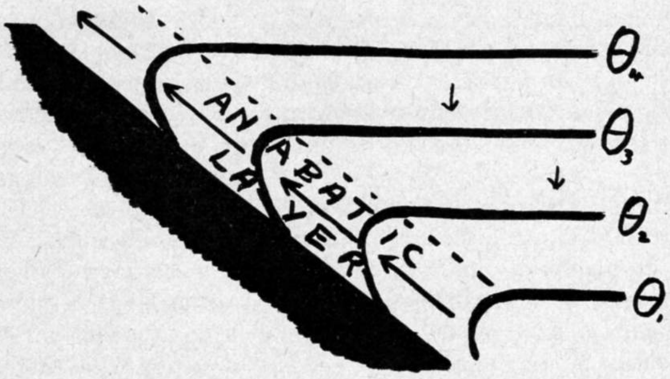


Fig. 1 – The horizontal lines indicate surfaces of constant potential temperature when the air is stably stratified. They are bent over close to the hillside when the sun shines, and the anabatic flow is confined to the warmed layer.

(iii) *The angle of the slope*. If the surface is flat there is no anabatic flow; if it is vertical the heating is confined to a thin layer even if there is no static stability; consequently there is an angle of slope, at present unknown, for which the anabatic flow has a maximum volume flux, and probably different angles for which there is a maximum momentum flux or width of stream above a given speed.

(iv) *The extent of the slope*. Although a situation can be imagined in which the depth of the anabatic layer had the same depth all the way up the slope, so that the mechanics of the motion were the same at all points, it would require a distribution of static stability and heating unlikely to occur in practice. In any case the observations of haze described below indicate that this cannot be the situation sometimes, and so the actual thickness and strength of the anabatic flow must depend very much on position on the slope as well as the other factors already mentioned.

2. The distribution of haze

On 2nd February 1957 there was an almost flat calm in the valley of the Durance in the neighbourhood of St. Auban (Basses-Alpes) and early in the morning the pollution from the Pechiney works was confined to a shallow layer about 50 metres deep except for some effluent from the tall chimney, (Plate I) which was at a higher level. The sunshine caused a steady rise of the low level pollution until it was well above the airfield, from which it appeared that thermals were gradually distributing it upwards.

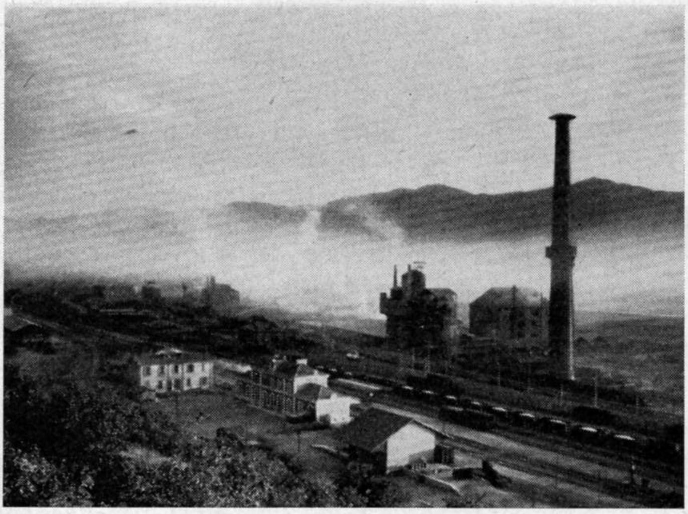


Plate I – Pollution collected in the valley bottom as a result of katabatic flow at night and the formation of a pool of cold air into which the pollution was emitted. Photo by R. S. Scorer

Soon, smoke was seen drifting from the tall chimney towards the north and this was described to me by one pilot as the "sea breeze" effect as the mountains warmed up in the sunshine. At about 14.30 I was taken up in a Storch aircraft fitted with a thermometer and we found that the haze was more or less uniform up to a very sharp haze top. This haze top was at the snow line on the mountains, and was very flat and uniform, indicating that there were no thermals reaching up to it. The temperature was uniform from about 100 metres from the ground up to 1100 metres where the haze top was, and this shows that the air was quite strongly stably stratified. It was smooth above 100 metres.

Since there were no sharp intermediate haze tops but a fairly uniform distribution of haze up to the snow line (Plate II a and b) it seems reasonable to infer that the pollution ascended the hillside in the anabatic wind and was spread horizontally at all levels. At the bottom of the slopes the anabatic wind was probably as deep as the convection layer over the valley bottom, but decreased in thickness as it ascended the mountain sides and ceased where convection ceased at the snow line. (Fig. 2.)

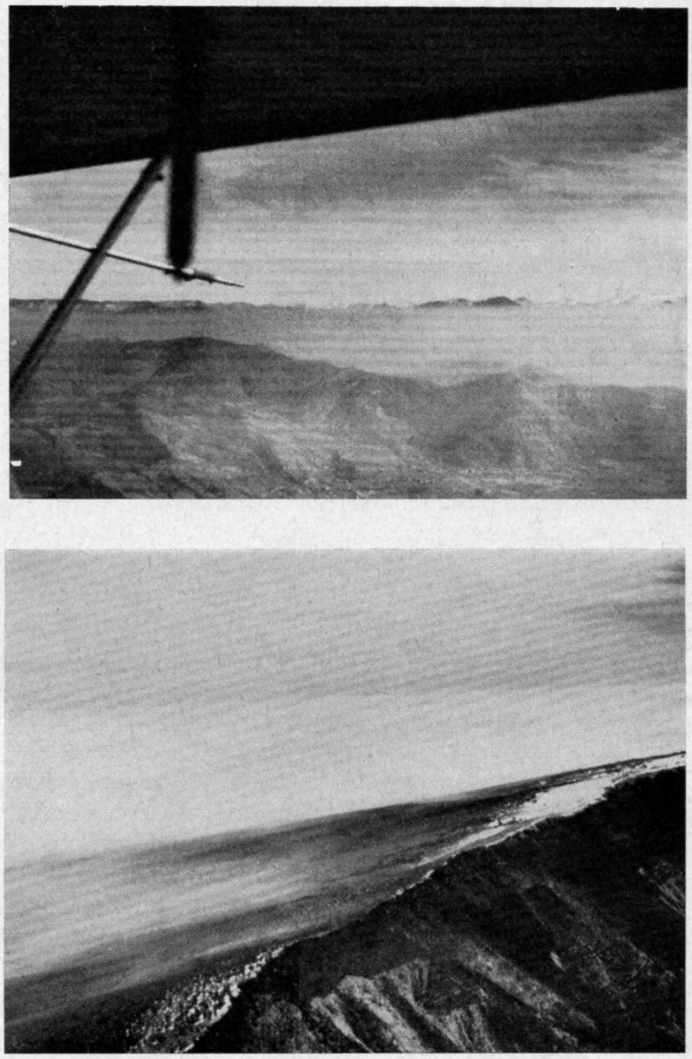
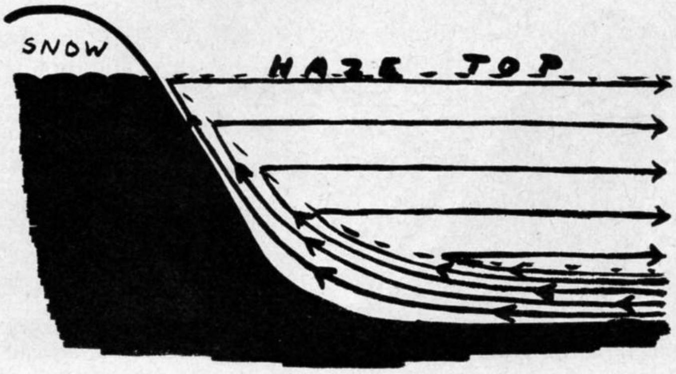


Plate II – On the afternoon of the same day as plate I the pollution was spread throughout the air mass up to the snow line by anabatic flow. The air was still stably stratified except for the bottom 100 m or so. Photo by R. S. Scorer

This occasion may not be typical of anabatic winds, and it is possible that the haze was spread out horizontally mainly during the period while the anabatic wind was developing; but I have not been able satisfactorily to envisage a flow pattern by which this could happen because the wind would develop all the way up the slope at the same time and not from the bottom upwards. In any case, if the wind on the slope penetrates a sharp inversion at all most of the current will pass on upwards without a noticeable layer of polluted air moving away from the hillside horizontally. There seems to be a continuous peeling off of anabatic air

Fig. 2 – The uniformity of distribution of haze in the air below the haze top is in conformity with a motion pattern as shown, in which the anabatic layer becomes gradually thinner as it ascends the hillside.



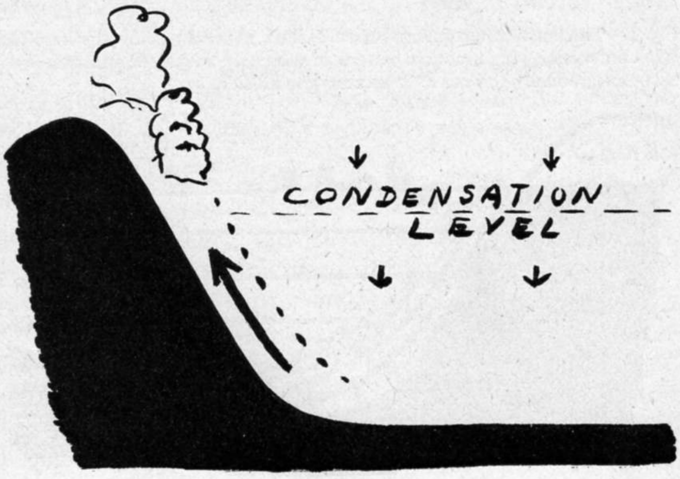
from the top of the upward flowing layer and in fig. 2, I have suggested that the layer is thereby decreased in thickness. The upcurrent is heated by thermals, which are turbulent and which penetrate through the anabatic layer and impinge on the stably stratified air mass above and partially mix with it, and so the top of the anabatic layer has a lower average buoyancy relative to the main air mass than the lower parts. Consequently some of it spreads out horizontally while the rest continues to ascend.

3. The statically stable air mass

It seems, from many observations, that the air over the low ground remains stably stratified all day when anabatic winds blow on the mountain slopes. Furthermore the anabatic flow feeds cumulus over the mountains and sometimes there are cumulus over the low ground early in the day but not later on although the ground temperature is much higher (See Scorer 1952, 1955). Therefore one naturally looks for mechanisms which will increase the stability of stratification in the air over the low ground and which are associated with the anabatic flow itself.

Since the only external influence is the heating of the surface, which is at the bottom of the air, the static stability at a fixed point can only be increased if the air there is replaced. As soon as a thermal reaches the condensation level during its ascent the additional heat derived from the condensed cloud makes it rise through an environment which is stably stratified for unsaturated air, and so the environment of cumulus clouds is always stable. If there is any downflow between clouds through the condensation level to compensate for the updraughts into clouds a sub-cloud inversion is formed by this sinking air, and this prevents the weaker thermals from ever reaching the condensation level. Anabatic flow through this stable layer may occur because the heat is put into the air on the hillsides at a higher altitude, and once this has begun the static stability of the air over the low ground is increased, and this in turn increases the anabatic flow. The consequence of this is that the thermals, usually in the form of cumulus, over the high ground *appear* to suck the air up the slopes into their bases, but it is really the subsidence of the air, and the stabilisation that it produces, that is responsible for the anabatic flow (Fig. 3).

Fig. 3 – Slow stabilisation due to subsidence takes place over the low ground and prevents the growth of cumulus there later in the day even though the ground temperature rises.



If there are cumulus over the mountains this does not necessarily mean that any anabatic flow up the slopes flows into them. A strong inversion sometimes acts as a lid to the anabatic flow of the lower slopes, and cumulus may yet be produced from thermals originating on the slopes which are above the inversion (Fig. 4).

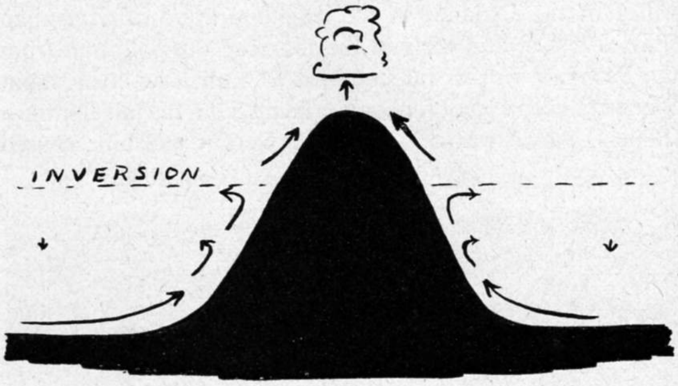


Fig. 4 – The presence of cumulus over mountains does not indicate that anabatic flow is continuous all the way up a slope: it may be interrupted by an inversion.

A "sea of cloud" below mountain top level indicates the presence of an inversion, and if it is thin enough for the sunshine to induce anabatic flow below it, the first part of it to disappear is that close to the mountain where the warming is most intense. The rest of the layer is probably warmed by subsidence and not by convective heating from below, and it disappears later. When a strong inversion exists below mountain top level, as it often does in the Red Sea area, swarms of desert locusts which remain airborne for a large part of the day get carried up to the level of the inversion and no further, and there have been cases of swarms being split with the two parts moving round different sides of the mountain.

If a sea of cloud is well below the snow line an anabatic circulation can easily develop on the slopes above as if the cloud layer were the ground; and it is important to note that because the daytime motion is set up by heating it can only take place above, and not below, the heat source.

4. "Evening thermals" and other phenomena

The "evening thermal" of Camphill was satisfactorily explained in a paper by Roper (1952) as a lee-wave phenomenon. Swiss soaring pilots, and others, have often found regions of rising air over valleys in the evening, usually with very smooth but rather slow ascent. It is tempting to explain these in terms of a counter current compensating for the katabatic winds which develop in the evening on the hillsides. There are two important considerations which show that this is not the correct explanation. First, the thickness of the katabatic wind is so small that the ascending motion over the much larger area of the valley produced by it is much too small to support gliders; and secondly, the ascending motion is often found at heights above the hill-top, and this could not possibly be produced directly by sources of cold at lower levels.

My own belief is that almost all evening thermals are lee waves, and it is necessary, to support this belief, to propose a mechanism which would start the wave motion in the evening. One possibility is that the stabilisation of the air mass by the cooling of the ground may change the airstream from one which does not execute lee-waves into one which does. If this were the mechanism the wavelength would be changing rapidly as the waves develop, and this does seem to be important in the development of the wave at Camphill, and was the sole mechanism proposed at the time Roper's investigation was made. A much more spectacular evening wave was reported at about the same time at Dunstable by Lee and Neumark (1952) whose gliders soared in it to more than ten times the hill height, and the onset of a katabatic wind immediately preceded the onset of the wave. The most obvious explanation is that the airflow was separating from the lee hillside as long as anabatic flow was present, and that as soon as katabatic flow set in the separation ceased because of the injection of momentum into the boundary layer. The upper air then began to execute waves determined by the ground profile which the streamlines had not been following during the day, (Scorer, 1958, p. 109 and p. 244).

Anabatic flow, therefore, when it occurs on a lee slope, is probably a much more important factor in destroying lee waves than the thermal convection which de-stabilises the lower layers of air. If the streamlines follow the ground the stability existing above the condensation level is usually sufficient to support waves. The onset of waves in the evening is often so rapid and spectacular that it cannot be due to the effect on the airstream of a gradual increase in the static stability of the lower layers.

5. *Model Experiments and observations needed*

Theory cannot advance at present beyond the routine of writing down the various physical factors which affect the anabatic flow and finding all the non-dimensional numbers which can be composed from them. (See for example Scorer 1958, p. 289.) Except in situations too simple to be useful there are two or more such non-dimensional numbers, if only because the angle of inclination, a, of the slope to the horizontal is one of them by itself. If $g\beta$ is the static stability of the air mass, a the thickness of the anabatic layer, V the mean speed and gB the mean buoyancy of the anabatic wind we obtain the following independent nondimensional numbers*

$$a, \frac{agB}{V^2}, \frac{a^2g\beta}{V^2}.$$

These are obtained on the assumption that the anabatic layer is of uniform thickness, velocity, and buoyancy over a very large area of hillside of constant slope, that the static stability is uniform within the air mass, and that a steady state is achieved. Obviously the problem is very complicated because for this simple case a curve relating the second and third of these numbers would have to be plotted experimentally for each value of a.

If a steady state is achieved there must be an exact balance between the buoyancy and frictional forces. The above considerations are only valid if the friction can be represented always by the same function of the velocity V, and if this is not the case at least one further nondimensional number is involved.


Plate III – Anabatic flow up a lee hillside above a sea of cloud in the Pyrenees made visible by cloud fragments

It is not surprising that the phenomenon of anabatic winds has eluded the grasp of theoreticians: there has not yet been any problem proposed which is both realistic and tractable. Because of its complexity no ready programme of experiments suggests itself. The purpose of this paper is to propose some ideas which will make the observation of anabatic winds in the field more profitable and intelligible.

The most important features which are worth recording seem to be the following:

(i) the stratification of the air mass,
(ii) the thickness of the anabatic layer,
(iii) the extent of it on the hillside and where it is limited by inversions,
(iv) what anabatic and katabatic flow changes accompany other, larger scale changes in the airflow,
(v) the position and duration of cumulus development on days when anabatic flow occurs.

Only in the confined valleys of Switzerland does anabatic soaring seem to have been carried out consciously to any extent (but see Davies 1951), but there are probably unexplored possibilities waiting to be exploited elsewhere as soon as pilots have a sufficient comprehension of the mechanisms to enable them to recognise the signs quickly and correctly.

References:

Davies, M., 1952, Thermal slope soaring at Camphill Gliding, Autumn 1951, p. 120.

Lee, G. H., and Neumark, O. W., 1952, A standing wave at Dunstable, Met. Mag. Vol. 81, p. 307.

Roper, D., 1952, Evening Waves, Quart. J. R. Met. Soc. Vol. 78, p. 415.

Scorer, R. S., 1952, Soaring in Spain 1952, Weather, Vol. 7, p. 373.

– 1955, The growth of cumulus over mountains, Arch. Met., Geoph., u. Biokl., Ser. A, Band 8, 1–2 Heft, p. 25.

– 1958, Natural Aerodynamics, Pergamon Press, London.

---

* β is defined as $-\frac{1}{\theta}\frac{\partial\theta}{\partial z}$ where 0 is potential temperature and z is the vertical length coordinate. β always appears multiplied by g because it has no physical importance except in a gravitational field. If $\Delta\theta$ is the temperature anomaly of the anabatic current, B is defined as $\Delta\theta/\theta$. Although B is another non-dimensional number it is, for practical purposes, always small and so its actual value does not affect the motion except through buoyancy forces: consequently it is always multiplied by g when it appears in formulae. This is equivalent to making the Boussinesq approximation by which density differences are ignored except when multiplied by g.

Zusammenfassung

«Anabatische» Winde entstehen, wenn Berghänge durch Sonneneinstrahlung erhitzt werden («Berg- und Talwinde»). Es bildet sich eine dünne Aufwind-Schicht am Berghang (anabatische Schicht). Die Luftmasse über dem Tal bleibt trotz der Sonneneinstrahlung stabil geschichtet. Die Linien gleicher potentieller Temperatur (denen die Luftteilchen folgen) sind nach dem Tal hin eingerollt (Fig. 1).

Der anabatische Wind und seine Schichtdicke hängt von einer Reihe von Faktoren ab, nämlich von dem Hangwinkel, der Hangoberfläche (Felsen, Vegetation, Schnee), der Orientierung zur Sonne, der Stabilität der Luftmasse usw.

Die Dunstverteilung im Tal lässt die Entwicklung des anabatischen Windes gut verfolgen. Am frühen Morgen liegt der Taldunst in den unteren 50 m (Tafel 1). Am Nachmittag hat die Dunst-Schicht die Höhe der Schneegrenze (1100 m) erreicht (Tafel 2a und 2b). Von 100 m Höhe bis zur Schneegrenze ist die Lufttemperatur über dem Tal konstant, die Schichtung also sehr stabil. Die Luft ist ruhig und enthält keine thermischen Aufwinde über der Talmitte. Trotzdem ist der Dunst in der ganzen Schicht gleichmässig verteilt.

Die einzige Erklärung ist, dass der Dunst von dem anabatischen Wind am Berghang hochgetragen und entlang den potentiellen Temperaturflächen in die Luftmasse eingemischt wird (Fig. 2).

Wenn sich Cumuluswolken über dem Hang bilden, wird die Stabilität der Luft über dem Tal durch Subsidenz verstärkt (Fig. 3). Wenn eine starke Inversion auf halber Hanghöhe aufliegt, können Cumuluswolken vom Hange abgelöst werden, selbst wenn der anabatische Wind die Inversion nicht durchdringt (Fig. 4).

Wahrscheinlich erklärt die Umkehrung dieses Vorganges die «Abend-Thermik». Wenn Abkühlung am Hange einsetzt, kehrt sich der aufsteigende anabatische Wind in den am Hang absteigenden «katabatischen» Wind um. Während der anabatische Wind Ablösung der Strömung über dem Leehang verursacht und damit Wellenaufwinde verhindert, liefert der absteigende katabatische Wind Impuls an die Grenzschicht und schafft die Vorbedingungen für Leewellen, wobei die Stromlinien den Bodenkonturen folgen können. Demnach kann man vermuten, dass die Abendthermik ein Wellenphänomen ist, wofür auch die schwachen, hochreichenden, ruhigen Aufwinde sprechen.

Modellexperimente und Segelflugbeobachtungen sind wünschenswert. Gewisse Modellzahlen können gebildet werden aus dem Hangwinkel, der Auftriebsgrösse, der Schichtdicke, der Strömungsgeschwindigkeit und der Luftmassenstabilität.

Anabatischer Segelflug scheint bisher nur in den Alpen bewusst durchgeführt zu werden. Was benötigt wird, sind quantitative Messungen, z. B. bezüglich der Stabilität der Luftmasse, der anabatischen Schichtdicke, der Gipfelhöhe der anabatischen Strömung, der Lage und Dauer der Cumuluswolken an Tagen mit anabatischem Wind und der Änderung der anabatischen und katabatischen Winde mit der Luftmasse.

(Swiss Aero-Revue 10/1967)