Investigation of Mountain-Valley Wind Circulation

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I. Introduction

The phenomenon of mountain and valley winds has long been of interest to glider pilots. It is, of course, very important for soaring in a clear day to understand wisely the complicated circulation pattern over mountainous terrain. Although there have been numerous theoretical studies about mountain-valley circulations, they are mostly restricted to thermally induced flows, without considering the interaction of surface motion with upper air motion. The understanding of this interaction is helpful to successful and safe soaring. The present investigation considers the non-linear interaction and the thermally induced flow near the ground surface over a typical undulating mountain-valley terrain.

II. Theoretical Model

The wind produced near the surface of a mountain slope (or the thermal origin) is called slope wind, which is attributed to differential heating between air near the slope and near the center of the valley. The simple, approximate slope wind solution can be obtained by solving simultaneously a set of linear differential equations which contains the simple momentum equations dealing with the balance between buoyancy force produced by differential heating and the eddy dissipation force near the surfaces, and the heat equation dealing with the balance between the heat advection and heat diffusion. When the upper gradient or geostrophic wind is taken into consideration over a complicated terrain such as a V-shaped valley however, a highly non-linear coupling through the advective and convective terms between the horizontal and vertical equations of motion and the heat conduction equation can no longer be neglected. As to the pressure term, the Boussinesq approximation is assumed, which means that the density variation is important only when it is associated with gravitational acceleration. This assumption is adequate for the boundary layer problem. In order to deal with the non-linear and complicated lower boundary surface, numerical integration of the set of finite difference equations mentioned above is most appropriate.

In the present model only the daytime case is treated in which it is assumed that there is no slip condition on the ground surface, i.e. the wind velocity is zero at the ground. The temperature condition at the ground is specified such that the deviation of potential temperature from the mean potential temperature at corresponding heights is –1.8 °K. The upper boundary conditions for the wind at the height of two and a half kilometers are assumed to be such that the cross-valley geostrophic wind is 10 m sec^{-1} and the up-valley and vertical velocities are zero. The potential temperature is finite at the upper boundary of two and a half kilometer level surface. The lateral boundary conditions for wind and potential temperature are assumed to be cyclic.

The physical feature of the terrain is assumed to be such that the height of the ridge is 500 m above the valley floor and the distance between ridges is 5500 m. The slope of the valley walls is assumed to be constant. The valley floor is assumed horizontal. The detail of the mathematics and methods of computation involved will not be discussed here. Since this research is still in progress, a complete report and further development will be presented in the near future.

III. Computed Results and Some Observational Data

From the model described above, the typical daytime cross-valley circulation is computed for one hour in simulated time. The results are shown in figures 1–3.

In these illustrations, the slope on the left-hand side represents the lee slope; the slope on the right-hand side represents the windward slope. Figure 1 shows the field of stream function. The basic flow is from left to right in the upper part of the domain. A separated circulation cell, however, is developed near the center of the valley to yield reverse flow from right to left next to the ground surface over the lower half of the lee slope. The center of this separated cell is situated above the lee slope at a level of approximately one-third of the ridge height based on the present assumed thermal condition on the slope and the upper wind condition on the top boundary. The thermally induced upslope wind in the daytime normally develops over both slopes near the surface all the way to the ridges when the synoptic scale wind is nearly calm. When the synoptic scale wind near the mountain ridge is appreciable, the upslope wind is destroyed on the upper portion of the lee slope and is reinforced on the upper portion of windward slope. The circulation in the lower half of the lee slope is also strengthened as compared with that at the symmetrical position in the valley above the windward slope. The horizontal wind speed in the reverse flow is thus higher. It is believed that the size and the intensity of the separated cell are directly proportional to both the upper wind intensity and the intensity of the upward heat flux or the temperature deviation from the mean on the ground surface for corresponding heights. That is, the higher either the upper wind velocity or the upward heat flux and/or temperature than the surroundings, the larger the size of the separated cell and the more intense the circulation. Figures 2 and 3 show the spatial distribution of horizontal and vertical velocities. It can be easily seen from these two figures that the upslope motion develops over both slopes near the center of the valley. On the upper part of the lee slope the flow remains downslope. The maximum reverse wind speed just above the lee slope near the valley center is approximately 3 m sec^{-1} for the present condition; the maximum wind speed in the upper portion is found to be about 11 m sec^{-1} at about 500 m from the ridge or 1100 m above the valley floor. Since the wind speed at the surface has to be zero, the maximum vertical gradient of horizontal wind is found just about the mountain ridges. Thus, the wind speed increases faster than any other location for the same vertical distance, say, three or four hundred meters above ground surface. The downward motion shown in figure 3 is found above the lee slope and it extends slightly beyond the center of the valley, reaching the bottom part of the windward slope. A thin layer having upward motion due to the return flow is situated between the lee slope surface and the deep layer having downward motion above. The maximum downward velocity is about 0.8 m sec^{-1} centered at about the 750 m level from the valley floor. Above the windward slope and the ridges the vertical motion is upward. The maximum upward motion is found at about 400 m above the middle of the lee slope or 750 m from the valley floor.

Among these computed results the most interesting feature is the development of the separated cell over the lee

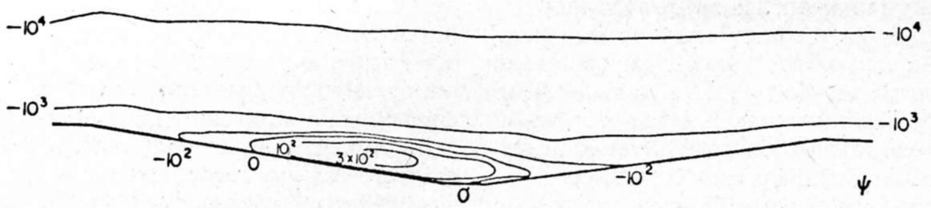

Fig. 1

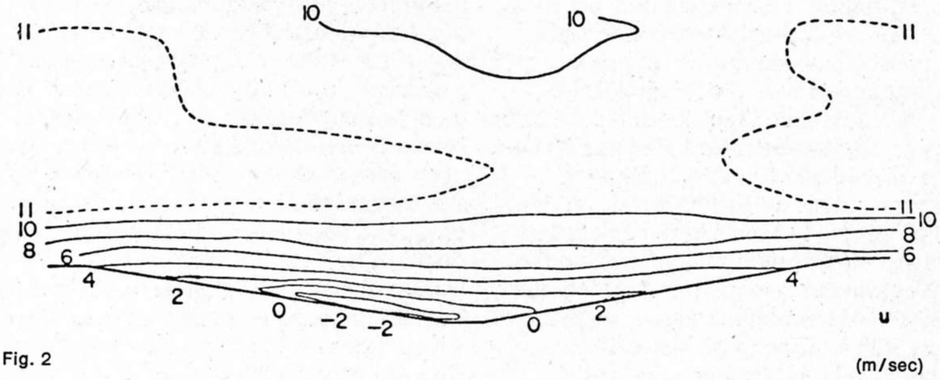

Fig. 2

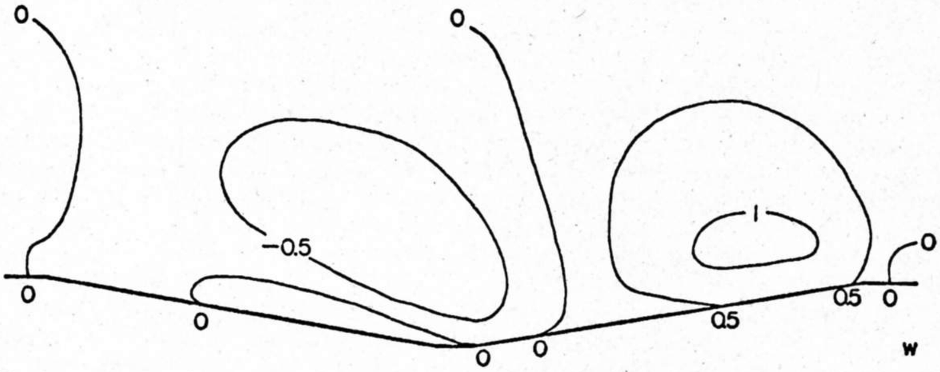

Fig. 3

slope which is essentially attributed to the non-linear interaction between the large-scale wind above the mountain and the thermally induced upslope wind in the valley. This phenomenon has indeed been found in mountainous country. A most interesting observation was reported by Ficker (1913) as shown in figure 4 depicting the trajectory of a balloon over the lee slope, involving two loops. The circulating cell was about 1 km long and 300 m high over the lee slope in a nearly V-shaped valley near Innsbruck, Austria. The balloon was trapped in the separated cell for about 8 minutes. The reverse flow in the lee on sunny days has also been observed in Vermont in 1959 where the author participated in the field observations.

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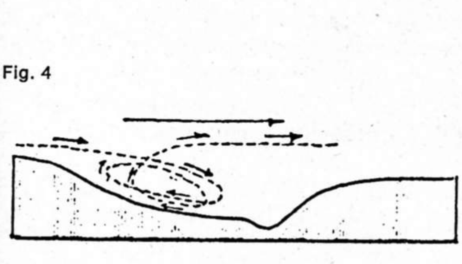
Fig. 4



Reference: Ficker, H. V., 1913: «Wirbelbildung bei Ballonfahrten im Gebirge». Meteorologische Zeitschrift, 48, 243–245.

Abstract

A theoretical model is developed to investigate the interaction between the large scale prevailing flow and the thermally induced cross-valley mountain-valley wind circulation. The Boussinesq approximation is assumed and the set of governing equations is integrated numerically. Under the strong convective condition in the day, it is found that a closed circulation cell is developed near the center of the valley. For the assumed mountain-valley terrain, the cell is extended half way to the ridgeline. The center is situated above the lee slope and is at a level of one third of the ridge height. The thermally induced upslope wind, together with the return flow, is developed over the lower half of the lee slope and covers the lowest part of the center of the valley. Thus, a small part of the lowest section of the windward slope is covered with return flow. When the wind at the 2500 m level is assumed to be 10 m sec^{-1} from the west, the maximum return flow is about 3 m sec^{-1}. On the windward side the background flow enhances the thermally induced upslope wind to cause a maximum vertical gradient of horizontal wind on the windward slope near the ridge, and the wind speed is higher than at any other point at the same vertical distance from ground surface. The maximum horizontal wind speed in the whole region is at a height of about twice that of the ridge line and is centered at a short distance on the lee from the ridge line. The vertical velocity is upward in a thin layer just above the lee slope and downward in a deep layer above the windward slope. The maximum downward flow is near the center of the valley at about 1 m sec^{-1}. The result is qualitatively in agreement with some observational data.

Résumé

Un modèle théorique a été développé dans le but d'étudier les influences réciproques du courant dominant à grande échelle et de la circulation d'origine thermique à travers et le long des vallées. L'approximation de Boussinesq est admise comme étant applicable et les équations qui s'y rapportent sont intégrées. On trouve que, dans des conditions de convection diurne intense, une cellule de convection fermée se développe au voisinage du centre de la vallée. Pour le terrain pris comme modèle, cette cellule s'étend jusqu'à mi-distance des lignes de crête. Son centre est situé sur le versant sous le vent et à un niveau atteignant un tiers de la hauteur de la crête. Le vent ascendant de pente, d'origine thermique, de même que le courant de retour, se développent au-dessus de la moitié inférieure de la pente sous le vent et concernent la partie inférieure du centre de la vallée. Ainsi, seule une petite partie de la partie inférieure de la pente au vent est affectée par le courant de retour. Si on considère un vent d'ouest de 10 m/sec à l'altitude de 2500 mètres, le courant de retour maximum est d'environ 3 m/sec. Sur le versant au vent, le flux dominant renforce le courant ascendant d'origine thermique sur la pente; il en résulte un gradient vertical maximum de la vitesse horizontale du vent au voisinage de la crête, sur cette pente au vent, et la vitesse du vent y dépasse celle qu'on pourrait observer en tout autre point, à la même distance du sol. La vitesse horizontale du vent la plus élevée dans toute la région, se

trouve à une hauteur qui est à peu près le double de celle de la ligne de crête et est située à faible distance et sous le vent de cette ligne de crête. Le mouvement vertical est dirigée vers le haut dans une couche mince juste au-dessus de la pente sous le vent et vers le bas dans une couche épaisse au-dessus de la pente au vent. Le flux descendant maximum est voisin du centre de la vallée avec environ 1 m/sec. Le résultat concorde qualitativement avec quelques valeurs observées.

Zusammenfassung
Zum Studium der gegenseitigen Einwirkung der generellen Luftströmung und der durch die Thermik hervorgerufenen quer und längs der Täler verlaufenden Winde, wurde ein theoretisches Modell entwickelt. Dabei wurde die Annäherung von Boussinesq als anwendbar angenommen. Die entsprechenden Gleichungen finden darin Anwendung. Es geht daraus hervor, dass bei intensiver Tages-Konvektion sich in der Nähe des Talmittelpunktes eine geschlossene Konvektionszelle bildet. Auf dem als Modell dienenden Gelände erstreckt sich diese Zelle bis auf halbe Distanz der Kretenlinien, wobei sich das Zentrum leeseits auf dem ersten Drittel der Kretenhöhe befindet. Der aufsteigende Hangwind thermischen Ursprungs sowie die Rückströmung entwickeln sich über der unteren Hälfte der Hang-Leeseite und sind nur im unteren Teil des Talmittelpunktes wirksam, so dass eigentlich nur der untere Teil der Hang-Luvseite der Rückströmung ausgesetzt ist. Wird nun eine Westwindströmung von 10 m/sec auf 2500 m Höhe angenommen, so beträgt die Rückströmung höchstens 3 m/sec. Auf der Hang-Luvseite verstärkt die herrschende Windströmung die Aufwinde thermischen Ursprungs, wodurch ein maximaler Vertikalgradient der horizontalen Windgeschwindigkeit in der Nähe der Krete und dem luvseitigen Hang entsteht. Es werden dort grössere Windgeschwindigkeiten als in irgendeinem Punkt gleicher Höhe gemessen. Im betreffenden Gelände wird die grösste horizontale Windgeschwindigkeit in einer Höhe, die ungefähr der doppelten Kretenlinienhöhe entspricht, gemessen. Sie befindet sich in geringem Abstand leeseits der Kretenlinie. Die vertikalen Winde strömen gegen oben in eine dünne Schicht oberhalb des leeseitigen Hangs und gegen unten unterhalb des luvseitigen Hangs in eine dichtere Schicht. Die maximale Abwindströmung beträgt in der Nähe des Talmittelpunktes ungefähr 1 m/sec. Das Ergebnis entspricht einigen qualitativ festgestellten Werten.