Airflow Characteristics in the Vicinity of an Obstructing Mountain Ridge in Complex Terrain

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Presented at the XVII. OSTIV Congress, Paderborn, Germany (1981)

I. Introduction

Airflow, or circulation patterns in the vincinity of mountains can be examined broadly in terms of two physical phenomena. Namely, the conversion of the available potential energy due to horizontal temperature gradients into the kinetic energies of mountain-valley and anabatic-katabatic slope flows. Secondly, the initiation or modification of circulation features through acceleration resulting from the vertical flux convergence of horizontal momentum, whether due to turbulent fluxes which move momentum down the vertical gradient or to wave momentum fluxes which may move momentum either against or down the gradient.

The difficulty of representation and analysis of airflows follows from the fact that thermal influences and momentum fluxes occur simultaneously, although at times one effect clearly dominates a given situation and can be approximately isolated for investigation. The magnitude of the Froude number (or Richardson number which is the inverse square of it, $Ri=1/F^2$) for example indicates the relative influence of forces exerted upon the air parcels as a result of buoyancy (temperature) effects and those exerted as a result of inertial (accelerations) motions (cf. Turner, 1973).

The Reynolds number measures the ratio of inertial forces to viscous (dissipation) forces. In all the situations discussed here the Reynolds number is very large so that the viscous forces can be neglected. The Froude number however is an important measure of the degree to which the airflow is modified by the physical structure of complex terrain or the thermal influences of the topography.

The general nature of thermally driven airflows in mountainous terrain has been described by Buettner (1967) and by Wooldridge and Orgill (1978). The dynamic structure of lee flows has been investigated by Kuettner (1959), Kuettner and Lilly (1968) and by Vergeiner and Lilly (1970).

This paper examines airflows in one particular location.

II. Methods and Procedures

Two regions north of Gunnison, Colorado, in the Rocky Mountain Plateau were selected for a limited study of atmospheric circulation features and dispersion characteristics in the planetary boundary layer. The valley locations ranged from 2600 to 2800 meters elevation, and mountain ranges and peaks in the area reached elevations exceeding 3800 m above sea level. The data discussed here were obtained near the small town of Crested Butte, Colorado, approximately 50 km north of Gunnison.

The observations of air motions were obtained through dual-theodolite tracking of temperature-sonde-equipped pilot balloons and mylar superpressure balloons. In the clear air of the Colorado Plateau, these balloons may be visually tracked to distances of 20 km unless terrain features intervene. Booker and Cooper (1965) have described the use of superpressure balloons to determine free air motion. The balloons act as accurate tracers of air motion since restoring forces are small and drag coefficients are high. Limitations to superpressure-balloon usage occur during large vertical excursions (greater than one kilometer) from their equilibrium density level or condensation on their surfaces. Advantages follow from their ability to trace air motions close to the surface and in the immediate vicinity of terrain features, where powered aircraft cannot safely operate.

Deviations of balloon trajectories from true airflows are mostly due to buoyancy forces acting on the balloons when they have been displaced vertically from their equilibrium density level. The observed balloon-tracking data used here were corrected for buoyant effects through application of the relationship:

$$-M\frac{\partial^2 z_B}{\partial t^2} - Mg + V\varrho g + C_D A\varrho(w_A - w_B)|w_A - w_B| = 0 \quad (1)$$

(Vergeiner and Lilly, 1970) where M is the mass of the balloon-ballast system,
z_B is the vertical displacement of the balloon,
g is the acceleration due to gravity,
ϱ is the atmospheric density
C_D is the balloon's drag coefficient,
A is the cross-sectional area of the balloon,
V is the volume of the balloon, and
w_B and w_A are the vertical velocities of the balloon and the air, respectively.

In the remainder of this discussion the vertical velocity w will be assumed to be w_A. Horizontal velocities of the air were taken to be the same as those of the pilot or superpressure balloons.

Vertical eddy diffusivity coefficients were derived from the vertical motion data by use of the relationship

$$K_{m,z} = \overline{w'^2}\, t_{L,w} \quad (2)$$

where $K_{m,z}$ is the vertical eddy diffusivity coefficient for momentum, w'^2 is the variance of the vertical motion, and $t_{L,w}$ is the Lagrangian time constant for the vertical motion. $t_{L,w}$ itself was deduced from the autocorrelogram of vertical motions for each superpressure-balloon run. The autocorrelation R(t) was assumed to have the form:

$$R(t) = A\exp(-t/t_L) + B\cos\omega t, \quad (3)$$

where A and B are constants and ω is the frequency of atmospheric waves present over the trajectory of the balloon. These waves were filtered from the autocorrelogram before fitting the curve to an exponential form to obtain t_L.

Vertical momentum fluxes were calculated for the horizontal components of the wind velocity u and v as the mean products of the component perturbations:

$$\overline{\varrho u'w'} \text{ and } \overline{\varrho v'w'} \tag{4}$$

with the perturbations taken with respect to mean values along the individual balloon tracks.

Froude numbers were calculated based upon level velocity and height above the surface as

$$F = \frac{u\,(z)}{\left[gz \left(\dfrac{\varrho'_0 - \varrho'(z)}{\varrho'_0} \right) \right]^{1/2}} \tag{5}$$

where u (z) is the wind speed at z metres above ground.

$\varrho'(z) = \varrho(z) \left(\dfrac{p(z)}{P_0} \right)^{\gamma}$ = local potential density at height z

ϱ'_0 = reference potential density
p (z) = atmospheric pressure at z
p_0 = reference pressure
γ = ratio of specific heats $\simeq$ 1.4 for air.

III. Observations and Results

A series of pilot and superpressure-balloon flights were completed over a period of six days in the vicinity of the town of Crested Butte, Colorado. The winds aloft blew steadily from 235° to 250° at speeds from 18 ms^{-1} to 25 ms^{-1} throughout this period, with clear skies except for occasional cumulus clouds over the mountain peaks and ridges. Figure 1 shows the terrain contours in metres above sea level and the balloon-launch sites for this field experiment. Three cases (3,5,7 June 1980) are discussed here.

3 June 1980

Observations were taken over a slope with a south aspect in the early daylight hours of 3 June 1980 in the vicinity of S1 in Figure 1. The synoptic chart for 500 mb showed a broad west-southwesterly flow (240°, 22 ms^{-1}) over Colorado at 0500 local standard time (LST), with clear skies. At the time of the first sonde-equipped pilot balloon at 0730 LST, the surface wind was light and variable, becoming light westerly (weak mountain wind) by 1100 LST.

The 0730 LST temperature sonde (Figure 2) showed the presence of a shallow inversion capped by a shallow neutral layer, and then stable air above 250 m at the launch site. Sunrise, with significant solar illumination of the surface, occurred at approximately 0500 LST. While the Froude number varied as a function of height above the terrain it tended to approach a relatively constant value by about 600 m above ground level in all stable cases. This value was 0.46 for this sounding; at 0500 LST, a Froude number computed from the (upstream) Grand Junction, Colorado, rawinsonde was 0.63. The wind speed showed a slight maximum at 900 meters above the valley floor and a minimum at 1100 m; above that, the wind increased in speed again.

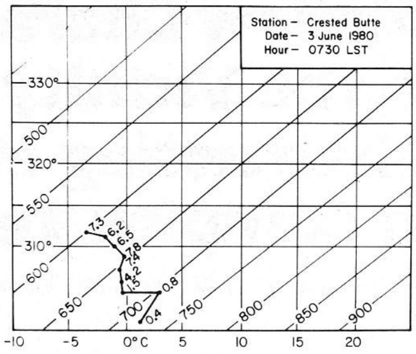

Fig. 2 Temperature soundings for 3 June 1980. The wind speed in ms^{-1} is given at observation points along the sounding.

The superpressure balloons launched in rapid sequence between 0703 LST and 0916 LST showed that the upslope flow was increasing in depth and intensity (Figure 3), with little evidence of flow in the valley direction. The vertical eddy diffusivities averaged 10 m^2s^{-1} for 0703, 0745, and 0916 LST flights at altitudes of 160–225 m above ground level (agl), but increased to 42 m^2s^{-1} by the 1008 LST superpressure flight at 350 m agl. The momentum fluxes were downward (average: −0.11 nt m^{-2} along the axis of the valley, but upward (average: 0.12 nt m^{-2}) along the slope, perpendicular to the axis, for the 0703, 0745, and 0916 LST flights combined. The 0864 LST temperature sonde (Figure 4) indicated a rapid evolution of the wind and temperature field had occurred since 0730 LST. The atmosphere was approximately neutral through a depth of 1200 meters, and a well-pronounced wind maximum was found at about 300 meters above the valley launch site. The surface valley wind was established at this time with a speed of 1.0 ms^{-1}. Above 600 m the wind was again increasing in speed with increasing altitude.

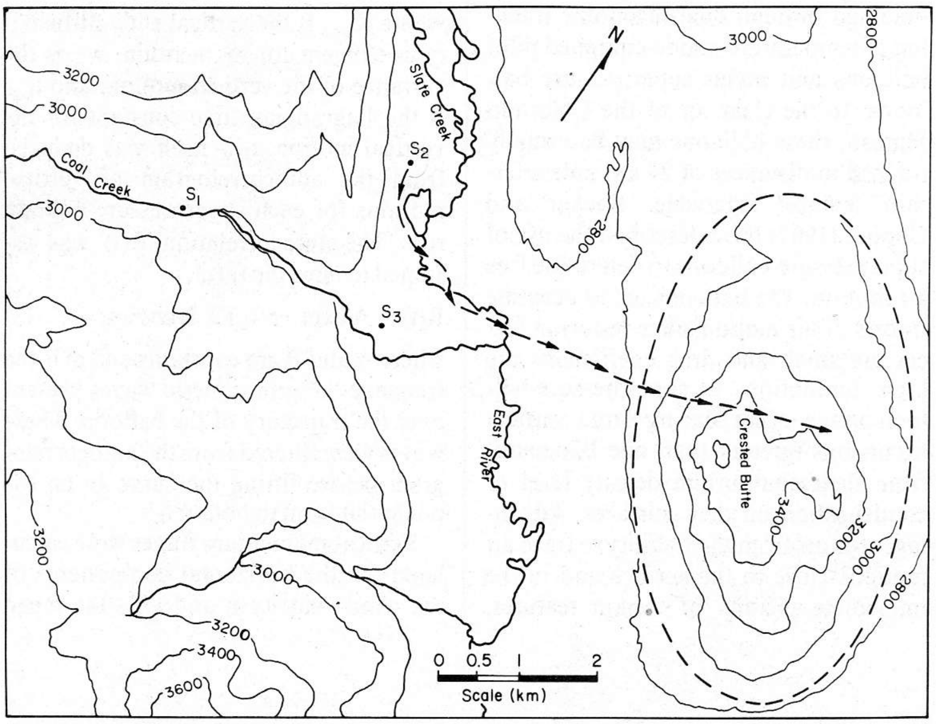

Fig. 1 Terrain contours in Crested Butte, Colorado, region. Heights are in meters msl; balloon launch sites are shown (S_1, S_2, S_3). Also shows horizontal projection of the 1710 LST, 5 June 1980, superpressure balloon trajectory.

7 June 1980

Morning observations taken near the mouth of Coal Creek Canyon (S3, Figure 1) illustrated the development of the daytime flow, with slightly different timing than on 3 June 1980. The 500 mb wind had shifted only slightly from 3 June, blowing from 250° at 18 ms^{-1}, again with clear skies. The surface mountain wind was weak, at 0.7 ms^{-1}.

The 0618 LST temperature sonde (Figure 5) showed an inversion of 3.7 °C, with a depth of 150 m. Above that, the lapse rate was neutral to about 500 m, and slightly stable at higher levels. The local Froude number approached 0.36

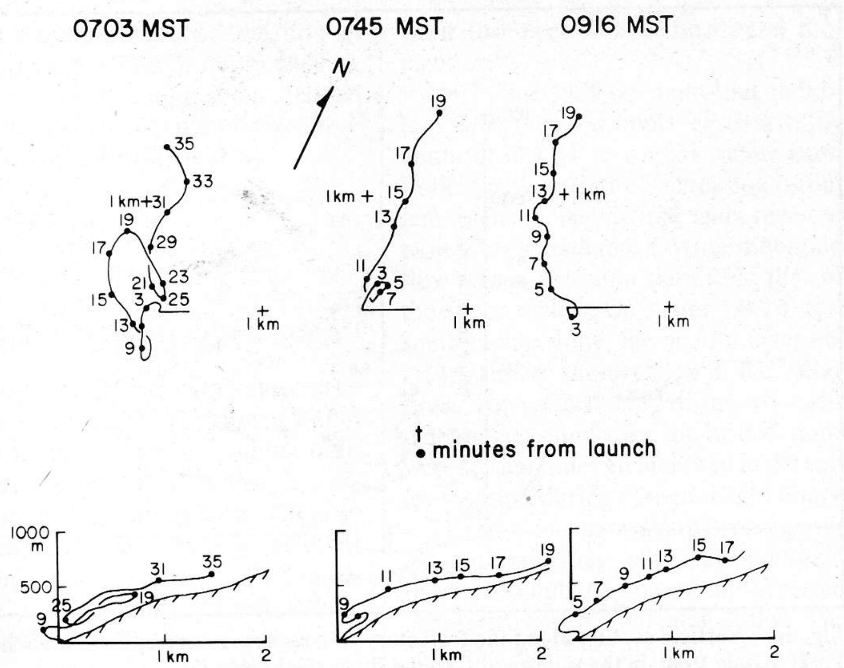

Fig. 3 Horizontal and vertical projections of superpressure balloon flights on 3 June 1980. Time from launch ist noted along each trajectory.

for this sounding; for the Grand Junction (Colorado)—rawin—sonde the Froude number was computed as 0.34. The wind speed decreased slightly to the top of the inversion, and then increased monotonically to the top of the sounding, 1400 m above the launch site. Three superpressure balloons launched between 0645 LST and 0850 LST showed very slight turbulence or air motion present in the lowest 350 m of the valley atmosphere. The vertical eddy diffusivity coefficient varied from 1.3 m^2s^{-1} at 60 meters to 7.5 m^2s^{-1} at 240 m, decreasing then to 4.8 m^2s^{-1} at 320 m. The second half of the 0850 LST balloon flight took place in the southwesterly flow near 720 m above the launch site, and showed an eddy coefficient of 21 m^2s^{-1}. The momentum fluxes were downward (average = -0.075 nt m^{-2}) along the valley axis, and not significant perpendicular to the axis at this site.

The 1012 LST temperature sonde (Figure 6) showed a marked change from the earlier sonde. The lowest 300 m was then unstable, with the remainder above 400 m essentially neutral to 1400 m agl. The lowest 900 meters showed little change in speed with height, but above 1000 meters the speed increased rapidly with increased elevation.

The flow structure was aparently quite similar betwen 3 and 7 June. There was a small discrepancy with regard to the timing of the onset of the surface valley winds which was most likely due to topographic differences in location between the balloon launchings on 3 June (S1) and on 7 June (S3). Although the two sites are only 2.5 km away, S1 is some 100-200 m higher and more sub-

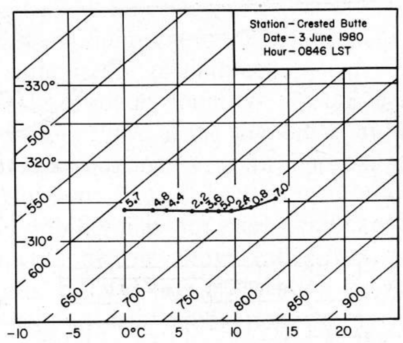

Fig. 4 Temperature soundings for 3 June 1980. The wind speed in ms^{-1} is given at observation points along the sounding.

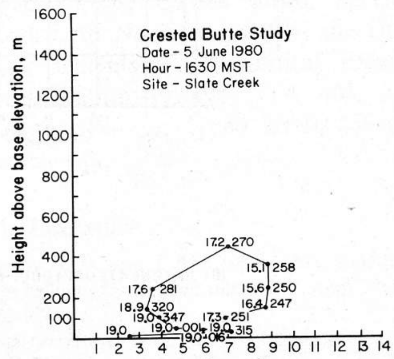

Fig. 5 Temperature soundings for 7 June 1980. The wind speed in ms^{-1} is given at observation points along the soundings.

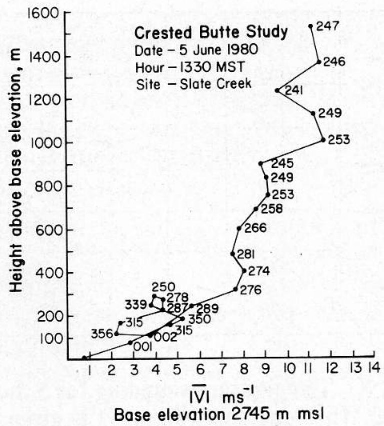

Fig. 6 Temperature soundings for 7 June 1980. The wind speed in ms^{-1} is given at observation points along the soundings.

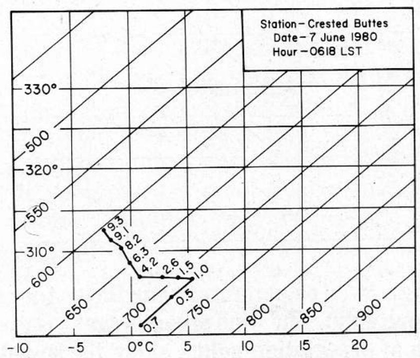

Fig. 7 Temperature soundings for 5 June 1980. The wind speed in ms^{-1} is given at observation points along the sounding.

jected to the immediate terrain influences than is S3 which is located in a relative accumulation zone along Slate Creek.

5 June 1980

Balloons were launched on the afternoon of 5 June 1980 at a site just north of the mouth of Coal Creek Canyon (S2 in Figure 1) in order to allow them to gain altitude in the lee of terrain to the west. The wind at 500 mb on this day was from 237° at 25 ms^{-1}, with clear sky conditions. At the time of the observation, a horizontal rotor with a vertical dimension of about 400 m was active in the launch area.

The rotor caused the temperature-sonde-equipped pilot balloon to rise to about 400 m and then descend (see Figure 7); the presence of a significant horizontal gradient of temperature was observed in the sounding. If one averages the temperatures at equal heights along the balloon track, an approximately neutral atmosphere is observed (Figure 8). An earlier pilot balloon (Figure 9), not sonde-equipped, identified a rotor in ap-

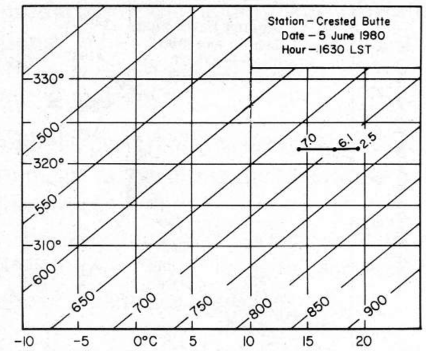

Fig. 8 Temperature sounding for 5 June 1980. The wind speed in ms−1 is given at observation points along the sounding.

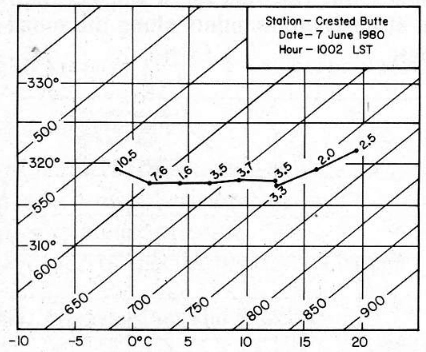

Fig. 9 Temperature soundings for 5 June 1980. The wind speed in ms−1 is given at observation points along the sounding.

proximately the same location. The pilot and superpressured balloons released on this site moved southward along the rotor and were then entrained into the flow near the mouth of Coal Creek Canyon (Figure 1), and approached Crested Butte Mountain from the direction of the prevailing gradient wind.

The trajectory of the airflow (Figure 10) calculated from the superpressure balloon released at 1710 LST 5 June was also subjected to the vertical motion present at the launch site, but did not complete a revolution of the rotor. Rather, it moved eastward to describe a wave of length about 1.3 km, and then rose to an altitude of about 820 meters, passing over the Crested Butte Mountain, not far from the highest part of the mountain. The «damping« of the wave motion near the base of the mountain may have been in response to a small terrain feature at the base of Crested Butte, which was approximately out of phase with the wave in the airflow.

The motion of the air over Crested Butte Mountain can be compared to potential flow over an ellipsoidal hill, as proposed by Hunt, Snyder, and Lawson (1978). The geometry of the proposed ellipsoid (see Figure 11) approximates that

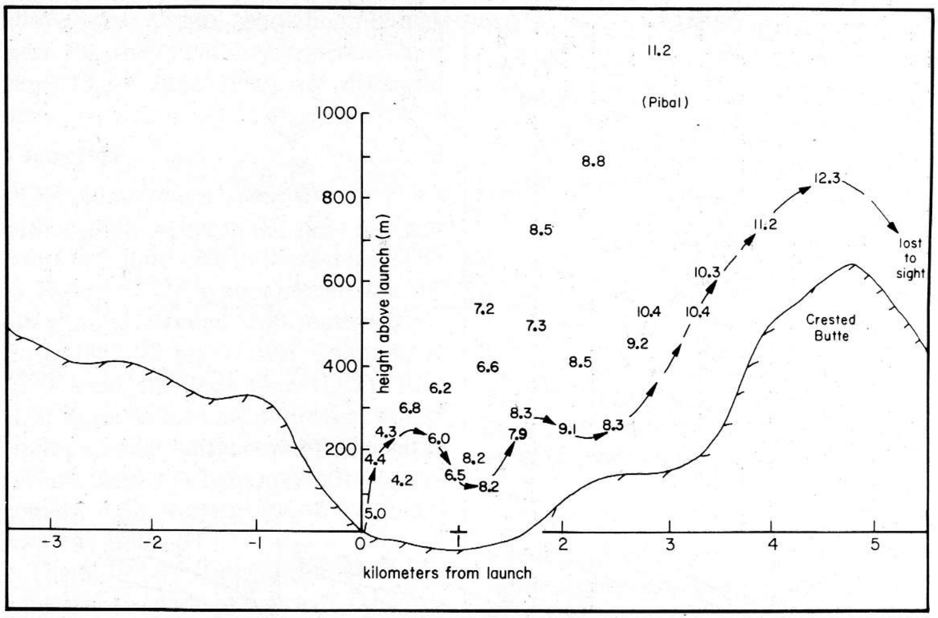

Fig. 10 Vertical section along the trajectory of a superpressure balloon launched 1710 LST, 5 June 1980, in the vicinity of Crested Butte, Colorado.

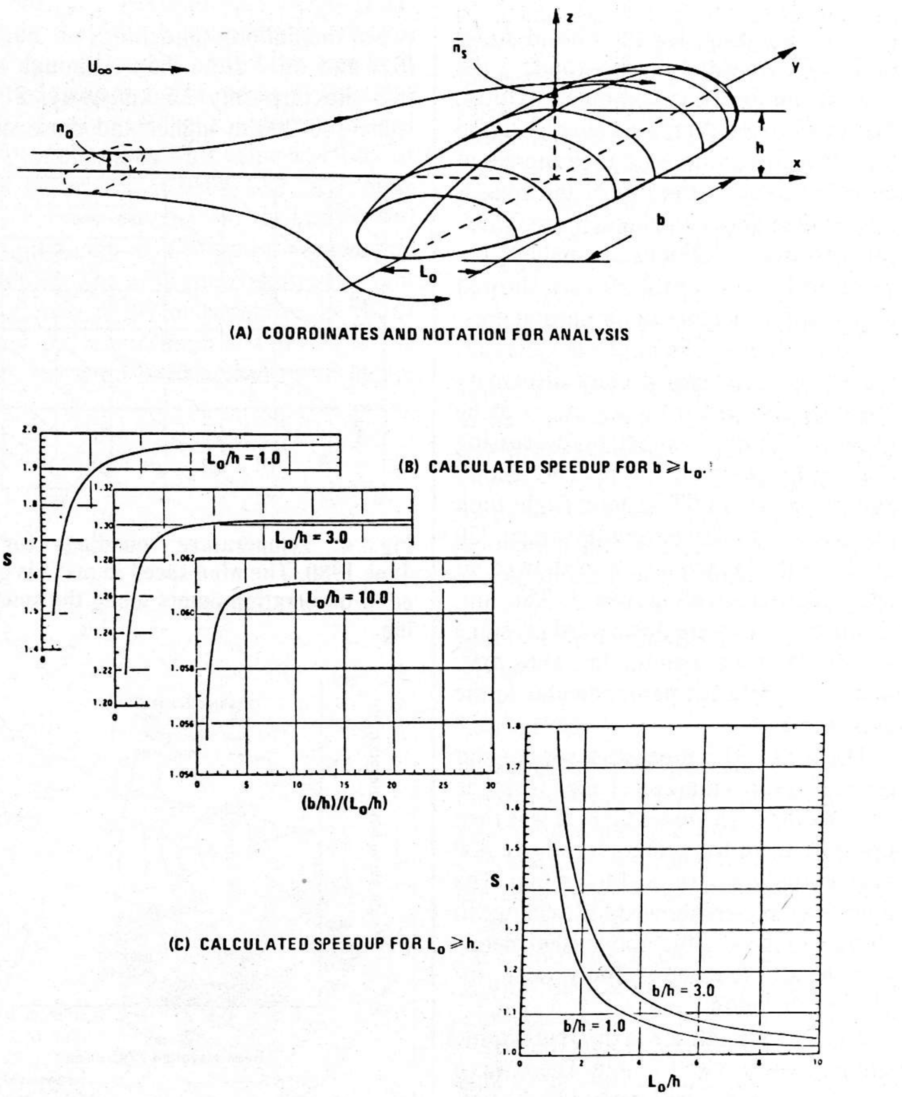

Fig. 11 Geometry of an ellipsoidal hill; airflow for a neutral atmosphere with uniform velocity and long fetch. From Hunt, Snyder, and Lawson (1978).

of Crested Butte (see dashed lines on Figure 1), where b = 3000 m, L_o = 1800 m, and h = 600 m. Hunt et al. defined «speedup» (S) of maximum flow velocity (U max) over the ellipsoid as:

$$S = \frac{U_{max}}{U_\infty(h)} = \frac{2}{2 - \beta_0} \qquad (6)$$

where

$$\beta_0 = \left(\frac{L_0}{h}\right)\left(\frac{b}{h}\right) \int_0^\infty \frac{du}{\sqrt{[(L_0/h)^2 + u]^3[(b/h)^2 + u](1+u)}} \qquad (7)$$

and the upwind flow U_∞ is assumed to be uniform with height. The upwind pilot balloon taken at 1330 LST did not indicate total agreement with this U_∞ assumption, but the winds from 300 m to 900 m above the launch site were not far from uniform, with a speed of 8.5 ms^{-1}.

From the dimensions of Crested Butte estimated above, equation 6 suggests a speedup of flow of 1.6. The speedup (S) estimated on the basis of wind data shown in Figure 10 for 5 June 1980 is about 1.5, remarkably close to the theoretical value when one considers the lack of agreement with the basic assumptions.

As a further test of agreement of field measurements with the theoretical treatment of Hunt et al. (1978), a calculation was made of the displacement of a «surface» streamline $\bar{n}_s$ from the ellipsoidal mountain in the x = 0 plane. An approximate relationship can be developed,

$$\bar{n}_s U_{max} P = \frac{b}{h} \frac{\pi}{2} n_0^2 U_\infty \qquad (8)$$

where the geometric parameters are as defined in Figure 11, which is valid only if $|x| \gg h$, b or L_0. P is the perimeter of the semi-ellipsoid in the plane x= 0; for the mountain it is about 7200 m. Estimating n_o = 200 m above launch site from Figure 10, the resulting $\bar{n}_s$ = 30 m. The measured trajectory, however, indicates that the streamline actually cleared the mountain by about 200 m; namely, there was no compression of the streamline from x = 0 to the mountaintop. Clearly $\frac{x}{b} \simeq 2$ is not sufficiently far upstream to experience any significant compression.

IV. Conclusions

The evolution of daytime valley-circulation features during morning hours on two clear June days illustrated the roles of thermal development, turbulent fluxes, and wind velocity at altitudes above the mountain ridges. The sequence of events proved to be: first, a rapid increase in the depth of the neutral layer near the ground; next, an increasing depth and strength of slope and valley winds; finally, an enhanced downward turbulent flux of horizontal momentum.

On 7 June 1980 the night-time mountain flow reversed under clear skies by about 0830 LST to a weak valley flow. Following a period of increasing turbulent intensity, the airflow again reversed to become a moderate daytime mountain flow whose direction paralleled that of the upper airflow. On 3 June 1980 over a south-facing slope, the neutral layer developed more rapidly than in the valley itself. The vertical eddy diffusivity coefficients measured over the heated slope were several times greater than in the valley location during early daylight hours.

The flow of a neutral atmosphere over an approximately elliptical mountain barrier exhibited some of the expected characteristics of potential flow. The speeding up of the air flow was slightly greater than that projected by theory; however, a single trajectory measurement appeared not to be compressed when passing over the barrier as expected from theory. The additional height of the trajectory may have been due to diabatic heating of the air along the trajectory, the presence of a wave in the early part of the trajectory, or to the closeness of the initial point to the mountain or to a combination of all three.

The Froude numbers of the early morning flows at the site and at an upstream location were in approximate agreement, suggesting that local effects on stability may not exert significant influence on the above valley-flow patterns. Should this observation be supported it has major implications for monitoring winds and dispersion above complex terrain.

V. Acknowledgements

The research discussed here was sponsored by the USDA Forest Service, Work Unit No. 2151, and by the Utah State University Agricultural Experiment Station Project UTA 403. Ms. Eleanor Watson typed drafts of the manuscript.

VI. Literature

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Charakteristische Eigenschaften einer Luftströmung bei Störung durch einen Gebirgszug in stark gegliedertem Gelände

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Luftströmungen bzw. Zirkulationen in der Umgebung von Berghindernissen können von zwei physikalischen Aspekten aus betrachtet werden. Zum einen ist die Umwandlung verfügbarer potentieller Energie infolge horizontaler Temperaturgradienten in kinetische Energie anabatisch-katabatischer Hangwinde bzw. Berg- und Talwinde denkbar. Zum anderen werden Beginn bzw. Änderungen von Zirkulationssystemen durch Beschleunigungsvorgänge hervorgerufen, die ihre Ursache in der Konvergenz des Vertikalflusses des horizontalen Impulses haben. Dabei können die turbulenten Flüsse Impuls entsprechend dem vertikalen Gradienten nach unten transportieren oder in den Impulsfluss einer Wellenbewegung überführen mit Impulstransport gegen oder mit dem Gradienten.

Die Schwierigkeit der Darstellung und der Analyse von solchen Luftströmungen rührt von der Tatsache her, dass thermische Effekte und Impulsfluss meistens gleichzeitig wirksam werden. Manchmal überwiegt einer der beiden Effekte und erlaubt dann eine isolierte Betrachtung der Einzelvorgänge.

Anhand von 2 Messbeispielen wird für den Fall einer einsetzenden Talwindzirkulation die Rolle der Aufheizung, der turbulenten Flüsse und der Windgeschwindigkeit in Höhe einer Bergkette bzw. darüber dargestellt.

Die gemessenen Vorgänge verliefen in folgender Reihenfolge:

a) schnelles Anwachsen der Höhe der neutralen Schicht
b) zunehmende Dicke der Hangwindschicht
c) zunehmende Stärke und Ausdehnung des Talwindes.
d) verstärkter turbulenter Fluss des Horizontalimpulses nach unten.

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