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METEOROLOGICAL OFFICE

Scientific Paper No. 18

Airflow around a Model of the Rock of Gibraltar

by J. BRIGGS, B.A.

LONDON: HER MAJESTY'S STATIONERY OFFICE

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SUMMARY

Wind-tunnel observations of the airflow around a model of the Rock of Gibraltar are used to indicate the turbulent areas. Reference is made to the relation of the patterns obtained to actual flow at Gibraltar.

INTRODUCTION

This investigation was undertaken in response to a request made by the Royal Air Force. The proximity of the Rock of Gibraltar to the runway at North Front can cause severe turbulence over the runway and its approaches. The operational procedures at present in use require the closure of the airfield when winds, measured near the control tower, exceed 25 knots and are between south-east and south-west (through south) though there is much doubt as to the reliability of the limits in use and also as to the best approach paths.

A previous survey of winds in the region of Gibraltar was reported by Field and Warden[1]* but that survey is not applicable to the present runway as it related to the landing of flying boats in the Bay of Gibraltar and was concerned with the effects of easterly winds. The Field and Warden survey consisted of wind-tunnel studies, using a scale model of the Rock of Gibraltar, followed by work at Gibraltar itself. For this present investigation it was proposed that wind-tunnel experiments should again be an essential preliminary to work at the site; the work of Field and Warden showed that the model studies could display important features of the flow patterns even though effects of wind shear and of temperature gradient were not simulated in the tunnel.

The aim of the investigation is to map out the areas of turbulent air, defined in this context as containing eddies of a size likely to affect aircraft, in the vicinity of the runway at North Front. Vertical gusts have a considerably greater effect on aircraft than equal horizontal gusts so the turbulent areas will be primarily those in which air movement in the vertical fluctuates considerably. The wind-tunnel work was therefore aimed at delineating areas of marked vertical fluctuations. This report is limited to the wind-tunnel work and the final assessment of airflow at the site itself must await later comparison with observations at Gibraltar.

APPARATUS

The original model of the Rock of Gibraltar, to a scale of 1 in 5000, used by Field and Warden, was available and was mounted on a plywood baseboard at a height of 6 inches above the floor of the wind-tunnel at Bracknell. The working part of the tunnel has a cross-section 4½ feet by 3 feet. The baseboard was 6 feet by 4 feet and was moveable along the length of the tunnel; its leading edge was faired to minimize disturbances set up by the board. The model rock was placed on the base at a distance varying from about one to two feet from the leading

*The superscript figures refer to the bibliography on page 7.

edge. A grid of 4.8-inch squares (equivalent to 2000-foot squares full scale) was superimposed on the board. Different wind directions were obtained by rotating the model on the base-board; in each case the grid was adjusted so that the runway remained the x-axis of the grid co-ordinates and the centre of the runway was the point of origin of the co-ordinates.

Airflow was made visible by the introduction of paraffin-vapour "smoke" into the tunnel. The smoke, produced by a generator built to the pattern described by O'Neill[2], was fed to a number of probes carried by a brass tube through the tunnel wall. The probes, of 3/16 in. diameter copper tubing, were offset from the supporting tube and the ends were tapered slightly to reduce turbulence due to the probes. A number of interchangeable probes were available so that either a single plume of smoke or a number of plumes could be observed. In the absence of the model rock the smoke plumes were steady and the dispersion only slight. At low tunnel speeds some puffiness of the smoke was noticeable; this puffiness, due to variations in the generator, was reduced by the introduction of a buffer in the form of a large reservoir between the generator and the probes.

It was found that smoke plumes closer to each other than about 2.4 inches (1000 feet full scale) could not easily be observed in turbulent regions so the bulk of the observing work was done with plumes at heights of 1.2, 3.6, 6.0, and 8.4 inches above the board (equivalent to heights of 500, 1500, 2500 and 3500 feet full scale).

OBSERVATIONAL PROCEDURES

Introduction of the model rock into the tunnel produced quite dramatic effects on the previously steady smoke plumes. In some areas the fluctuations of the smoke were extremely wild and in these disturbed areas slight changes of position of the probes could produce large changes in the violence of the fluctuations; similarly, pronounced upward currents were replaced by strong downward currents in very short distances.

In preliminary trials it was found that the pattern of the airflow remained almost unchanged for tunnel speeds between 10 and 60 knots. Below speeds of 10 knots, observations were difficult due to puffiness of the smoke whereas above 60 knots the smoke was less dense and so again more difficult to observe. It was decided to adopt a constant tunnel speed of 20 knots for the main experiments.

Subjective estimates of the turbulence in the vicinity of the rock were based on visual observation of the degree of oscillation of the smoke plumes in the vertical plane. The smoke plumes were viewed horizontally and the following scale was used to assess the turbulence:

- air smooth: no perceptible change from the plumes obtained in the absence of the model,
- slight turbulence: occasional oscillations of the plumes just perceptible,
- moderate turbulence: variations of the plume direction in the vertical plane exceeding about 20°,
- rough air: variations of the plume directions in the vertical plane exceeding about 40°.

The estimates were based on movement of the smoke at about one inch from the probe outlets. At points farther from the probes, the plume fluctuations were a measure of the total turbulence between the probe and the point rather than at the point and, very near to the probe, the oscillations were reduced by the speed of issue of smoke from the probe.

Although the turbulence assessment was subjective, it was found that repetition by the same or by a different observer gave almost identical results. The probe positions were readable to an accuracy of about 0.5 inches (200 feet full scale) and movements of this order were quite sufficient to reveal substantial variation in the amplitude of fluctuations. Indeed the separation of rough from smooth air was found to be generally quite sharp.

Visual estimates were made of the mean positions of the smoke plumes, these estimates being helped by the automatic averaging performed by the plumes, the mean position being indicated by the denser smoke at the centre of the plume. The mean angular deviation of the plume from the horizontal was estimated to one degree and again generally consistent results were obtained.

RESULTS

The turbulent zones were delineated at four levels (500, 1500, 2500 and 3500 feet) for five main wind directions (120, 150, 180, 210 and 240 degrees from north). Figures 1 – 18 depict the patterns obtained. Each diagram shows the boundaries of the turbulent zones (full lines) and also isopleths of mean departure of the air currents from horizontal in degrees, positive upwards, negative downwards (dashed lines). Simplified diagrams of flow, in the horizontal plane, at the 500-foot level are presented as Figures 19 – 23. The variation of the zone of rough air with wind direction is shown, by Figure 24, for the 1500-foot level. The five main wind directions and the supplementary directions of 110° and 250° are illustrated.

Sketches of smoke plumes are presented as Figures 25 and 26.

DISCUSSION

Relation of the flow round the model to flow around the Rock of Gibraltar

If the air is in neutral stability and if it is possible to neglect viscosity effects then, for both the model and the Rock, the flow is defined by equations of the form:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x}, \qquad (1)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial y}, \qquad (2)$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z}, \qquad (3)$$

$$\text{and } \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (4)$$

The effect of the rotation of the earth has been ignored here since the scale of the phenomena concerned is, at most, three miles.

The density, ρ, may be regarded as approximately constant, equal to ρ_o, for the shallow layers studied. If the typical length scale of the motion is L and the typical velocity scale is U then we may define non-dimensional variables as follows:

$$x' = x/L, \quad y' = y/L, \quad z' = z/L,$$
$$u' = u/U, \quad v' = v/U, \quad w' = w/U,$$
$$t' = \frac{U}{L}t,$$
$$p' = \frac{1}{\rho_o U^2}\cdot p, \quad \rho' = \rho/\rho_o,$$

where dashes denote the non-dimensional variables. Transforming equation (1) using these relations we get:

$$\frac{U^2}{L}\left[\frac{\partial u'}{\partial t'} + u'\frac{\partial u'}{\partial x'} + v'\frac{\partial u'}{\partial y'} + w'\frac{\partial u'}{\partial z'}\right] = -\frac{U^2}{L}\cdot\frac{1}{\rho'}\cdot\frac{\partial p'}{\partial x'}$$

$$\text{or } \frac{\partial u'}{\partial t'} + u'\frac{\partial u'}{\partial x'} + v'\frac{\partial u'}{\partial y'} + w'\frac{\partial u'}{\partial z'} = -\frac{1}{\rho'}\cdot\frac{\partial p'}{\partial x'},$$

so that the equation is unchanged in the new variables. Similarly equations (2), (3) and (4) are unchanged. This implies that, given the shape of the geometrical boundaries, the flow is uniquely determined, for model and natural flow, by the relevant non-dimensional quantities. Thus, if typical scales for model and real flow are indicated by suffixes m and r respectively, eddy velocities in the model and those in the real flow are related by the equations:

$$(u, v, w)_{model} = U_m \times (u', v', w')$$

$$\text{and } (u, v, w)_{real} = U_r \times (u', v', w'),$$

or eddy velocities need only to be scaled in proportion to the ratio of velocity in the tunnel to that in the atmosphere. Alteration of the velocity scale but not the length scale merely alters the eddy velocities in the same proportion as the velocity scale so that the pattern of flow is unchanged. The wind tunnel experiments provided some confirmation on this point for the flow pattern remained insensitive to speeds varying between about 10 and 60 knots. It is important to note that the time scale of the fluctuations is changed; if the time scale of the model is t_m, that of the real flow t_r, then we have:

$$t_m = \frac{L_m}{U_m}t' \text{ and } t_r = \frac{L_r}{U_r}t'$$

$$\text{or } t_m = \frac{L_m}{L_r}\cdot\frac{U_r}{U_m}\cdot t_r.$$

The above argument has neglected viscosity. To determine if viscosity may justifiably be neglected it is necessary to examine whether the viscous dissipation of eddies, on the scale we need to consider, is large enough to be effective during the time in which the eddies remain inside the area of interest.

Both over the Rock and over the model, eddies are likely to develop over a wide range of scales but it is probable that the greatest amount of energy is put into eddies on a scale comparable with the irregularities of the Rock (or model). It is these eddies which will be of main interest to aircraft. Smaller-scale eddies will occur but below a scale of about 200 feet for the Rock, or of about ½ in. for the model, the eddies are not likely to be of much interest. Also at this small scale the Rock is little rougher than any other land surface or the model little rougher than the tunnel walls.

Suppose the airstream for the model has a mean velocity, U, the area of interest has a maximum length, L, and it is necessary to consider eddies with dimensions down to L/d. The kinematic viscosity coefficient is ν. Then the rate of dissipation of energy due to viscosity is proportional to $\nu\left(\frac{\partial u}{\partial n}\right)^2$ where u is the velocity at a point and $\frac{\partial u}{\partial n}$ is the corresponding velocity gradient. For an eddy of size L/d, $\frac{\partial u}{\partial n}$ is given approximately by ud/L and the rate of dissipation of energy becomes $\nu\ u^2d^2/L^2$. But the initial energy is proportional to u^2. Thus the life of the eddy is given approximately by $u^2/\nu(u^2d^2/L^2)$ or $L^2/d^2\nu$. The eddy remains in the area of interest for a time L/U. Thus the viscous dissipation is not important if

$$L^2/d^2\nu \gg L/U,$$

that is, if

$$LU/\nu \gg d^2$$

or the Reynolds number is much greater than d^2. Taking $L = 2$ ft, $d = 50$ (corresponding to minimum eddy size of about $\frac{1}{2}$ in.), $U = 30$ ft sec^{-1} and $\nu = 1.076 \times 10^{-3}$ ft^2 sec^{-1}, this condition is clearly satisfied and we may infer that the viscosity has little material effect on flow around the model. For the real flow around the Rock it is obvious that molecular viscosity is unimportant but in this case the eddy viscosity associated with eddies already present upstream might have a similar effect. Taking, instead of ν, an eddy viscosity coefficient $K = 100$ ft^2 sec^{-1} then if $L = 10{,}000$ ft and $U = 30$ ft sec^{-1},

$$\frac{LU}{K} = 3 \times 10^3 > 2500 \; (=d^2)$$

so that, at least for upstream values of K up to 100 ft^2 sec^{-1}, little effect on the downstream flow is to be expected.

It seems reasonable to infer from the above arguments that the flow over the Rock itself should be deducible from the observed flow over the model, provided it is recognized that the time scale of the observed fluctuations must be changed appropriately.

Flow round the runway shown by the model

Figures 1–18 suggest that there is generally a zone of rough air which extends for some three miles or more downwind from the Rock. The roughest air is between the levels of 500 and 1500 feet and there is always a decrease at 2500 and 3500 feet though rough air is still found up to 3500 feet for winds of 120° and 240°. As the height increases the rough air is displaced further from the Rock, the air in the disturbed area moving around a vortex with nearly horizontal axis.

The direction of rotation around the vortex is indicated by the isopleths of mean departure from the horizontal; for example, in Figure 2, ascent is shown on the eastern side of the zone of rough air whilst descent is shown on the western side so that the vortex has a counter-clockwise rotation, looked at from the Rock. The troubled area is due to merging of the currents which sweep round the two sides of the Rock and the direction of rotation around the vortex at the centre appears to be determined by the relative speeds of the two currents. In each case the current which is least impeded by the Rock is the current which ascends. Thus the vortex is counter-clockwise for winds of 120° and 150° but is clockwise for winds of 210° and 240°. The vortical motion is perhaps more easily seen in the sketches of Figures 25 and 26; for example, Figure 25(*a*) shows the air sweeping up from 500 to 2500 feet in a distance of about 4000 feet, whereas air starting at 1500 feet descends near to the surface in an even shorter distance; at the same time Figure 25(*b*) shows the air at 500 feet deflected to the left and that at 1000 feet deflected to the right of the steady wind direction.

The wind direction of 180° is somewhat exceptional. This wind is almost along the main ridge of the Rock and the vertical displacement of air is at a minimum whilst the lateral displacement is also slight. No rough air, as defined above, is observed and flow at 2500 feet and above is almost unaffected by the Rock. A weak counter-clockwise vortex is shown by Figure 9.

As might be expected, the extent of the rough air increases as the wind blows more across the main ridge of the Rock; Figure 24 shows this effect. The total area of rough air is greatest for the winds of 110° and 250° but considering the runway, or line of approach to the runway, the extent of rough air seems likely to be at a maximum near the directions of 120° and 240° for there is a sharp decrease in turbulence near the end of the runway as the wind veers from 240° to 250° or backs from 120° to 110°.

For a tunnel speed of 20 knots a departure of $\theta°$ from the horizontal corresponds to a vertical current of approximately 0.35 θ knots (θ being small) so that the observed mean departures indicate mean vertical currents of magnitudes up to about seven knots. The variations about the mean indicate vertical gusts which may considerably exceed the tunnel speed.

Small changes in the direction of prevailing wind have relatively large effects on the mean vertical current at a given point. For example, considering the west end of the runway, Figures 1–4 show rising air in a wind of 120° whereas Figures 5–8 show descent for a wind of 150°. Similarly, at the east end of the runway, Figures 11–14 indicate strongly rising air when the direction of the wind is 210° whereas Figures 15–18 show only slowly rising air, even descending at 500 feet, when the wind is from 240°.

The shift of mean vertical current across the axis of trouble is especially notable at the 500 and 1500-foot levels. Considering Figure 1 it seems that an aircraft approaching the runway, with a wind from 120°, will experience a sharp change from descending to ascending air at a height of 500 feet and at about 2000 feet from the runway. Similarly, Figure 12 shows a sudden shift from descent to ascent at a height of 1500 feet and some 700 feet from the runway on the approach, with a wind from 210°.

Figures 19–23 suggest some important features of the low-level winds. Thus in Figure 19, for a general wind direction 120°, the 500-foot wind at the west end of the runway, the touch-down point, is a full cross wind whereas over most of the runway the wind is only 30° from the line of the runway. A similar effect is shown by Figure 22 for the east end of the runway and a wind from 210°.

The full implications of these diagrams for aircraft landing at Gibraltar are for operational authorities to decide but it is suggested that they do indicate the probable best approach paths. For example, the line of approach recommended in current (1962) regulations has been entered on Figures 11 and 15 for winds of 210° and 240°, respectively. The path recommended for 240° is clearly likely to avoid the roughest air whereas that for 210° is likely to encounter more turbulence than a normal straight approach.

CONCLUSION

Wind-tunnel studies of the airflow around a model of the Rock of Gibraltar have shown features which, if reproduced in corresponding full-scale flow, could be summarized as:

(i) The zone of turbulence in the lee of the Rock of Gibraltar extends for upwards of three miles downwind of the Rock and to heights of above 3500 feet. The turbulent zone is due to the merging of the streams which sweep round the two faces of the Rock and the axis of the zone extends, for winds between south-east and south-west, away from the north face of the Rock in the line of the prevailing wind.

(ii) The intensity of the turbulence, which is at a maximum between 500 and 1500 feet, increases as the wind blows more nearly perpendicular to the main ridge of the Rock, but in the vicinity of the runway at North Front most turbulence occurs for winds of about 230° and 120°.

(iii) In addition to the turbulent fluctuations of vertical velocity, which can exceed the prevailing wind speed, the velocity field shows areas of predominant upward or downward motion. These areas, though localized and varying in position with change in the direction of the prevailing wind, are sufficiently extensive to be important to aircraft. A traverse from one such area to another would produce a sudden change in vertical velocity which could cause the aircraft a severe bump.

It has been inferred that the real airflow should indeed correspond to the model flow, provided the air is in neutral stability. However, it is clearly necessary that the validity of the application of the model results to the Rock should be assessed by measurements at Gibraltar. On-site delineation of the velocity fields will require many observations. Since the adverse winds considered in this report are, fortunately for the operation of aircraft, relatively infrequent, the accumulation of sufficient data would take a very long time if ground-based measurements (for example, pilot balloons, smoke-trail observations etc.) were to be used. However, an aircraft could be used to carry recording instruments quickly through the whole area of interest and the pattern of turbulence could then be more readily established. There would also be an advantage because the effects of the airflow would be indicated fairly directly by the behaviour of the aircraft, whereas other methods would require translation into effects on aircraft.

ACKNOWLEDGEMENT

The author is indebted to Mr. J. S. Sawyer for advice concerning the relationship between the model flow and full-scale airflow.

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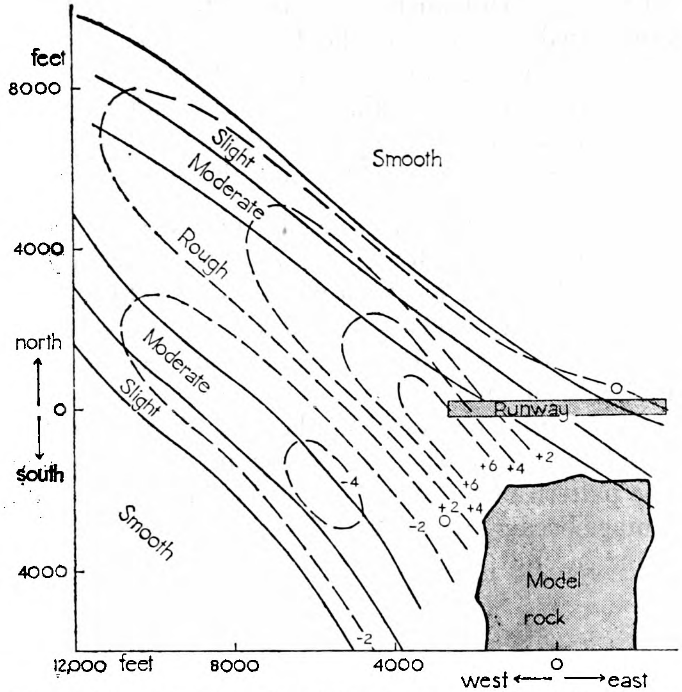


FIGURE 1. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal–height 500 feet, wind 120°.

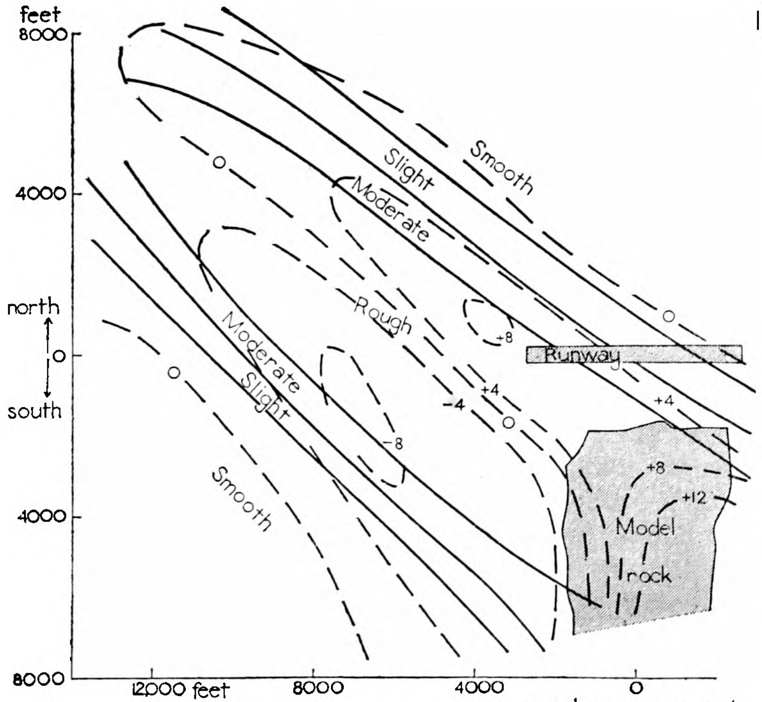


FIGURE 2. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal–height 1500 feet, wind 120°.

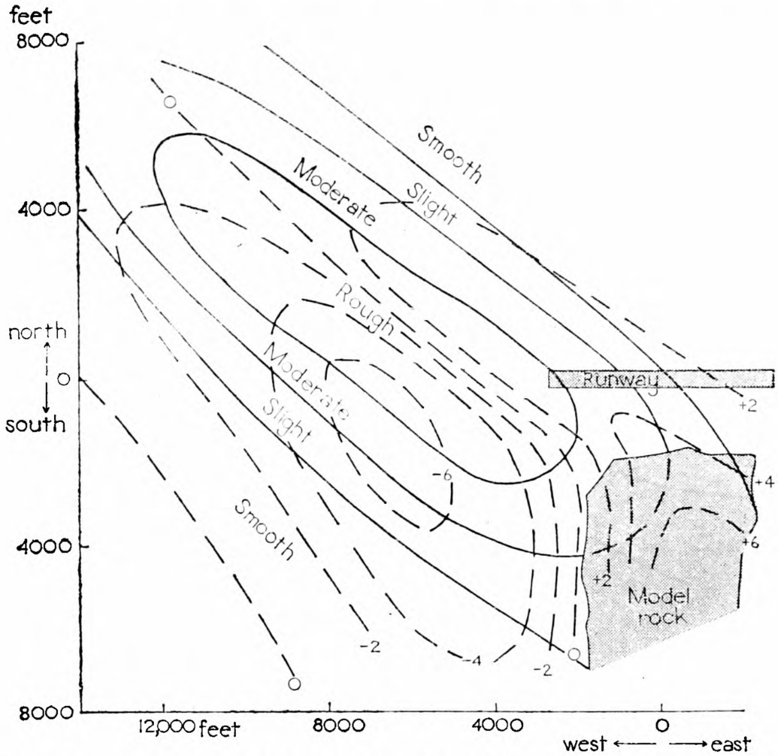


FIGURE 3. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal-height 2500 feet, wind 120°.

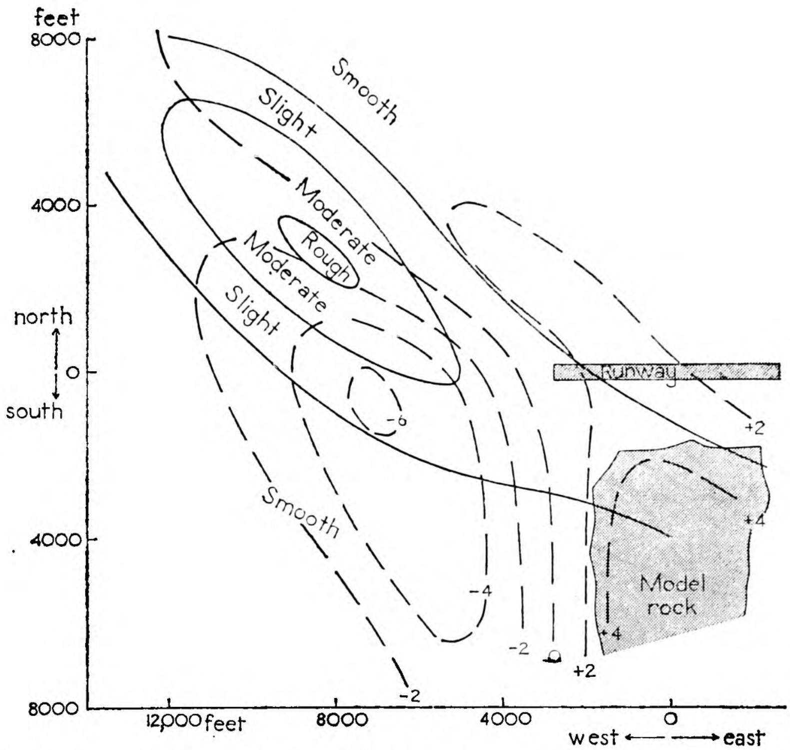


FIGURE 4. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal-height 3500 feet, wind 120°.

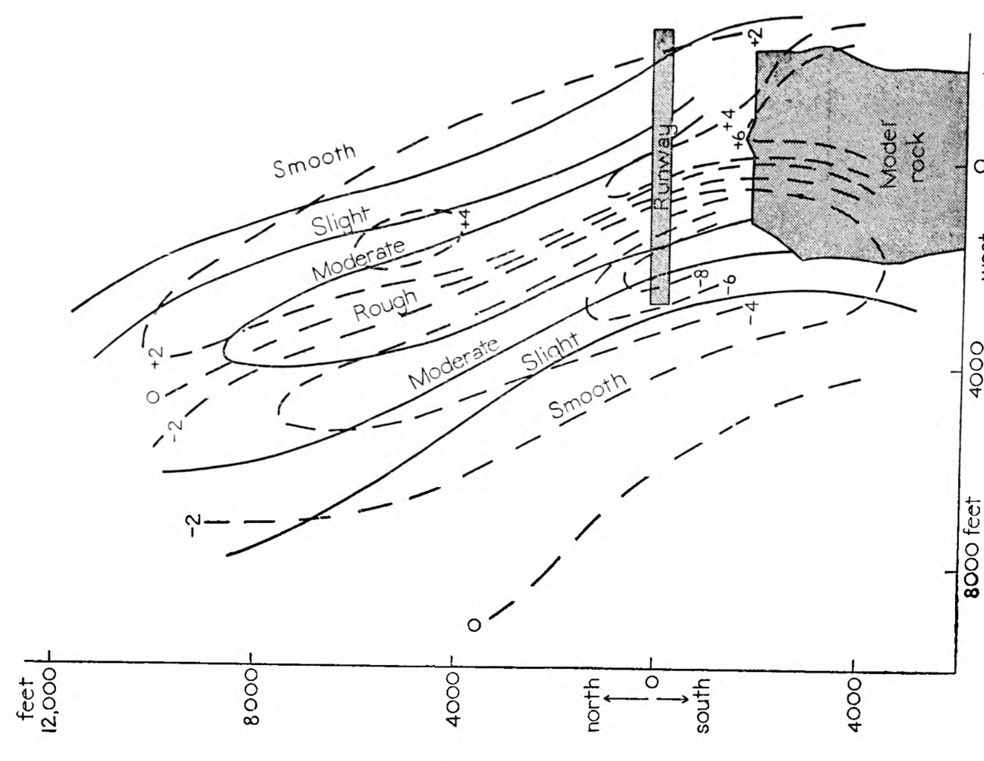


FIGURE 6. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal-height 1500 feet, wind 150°.

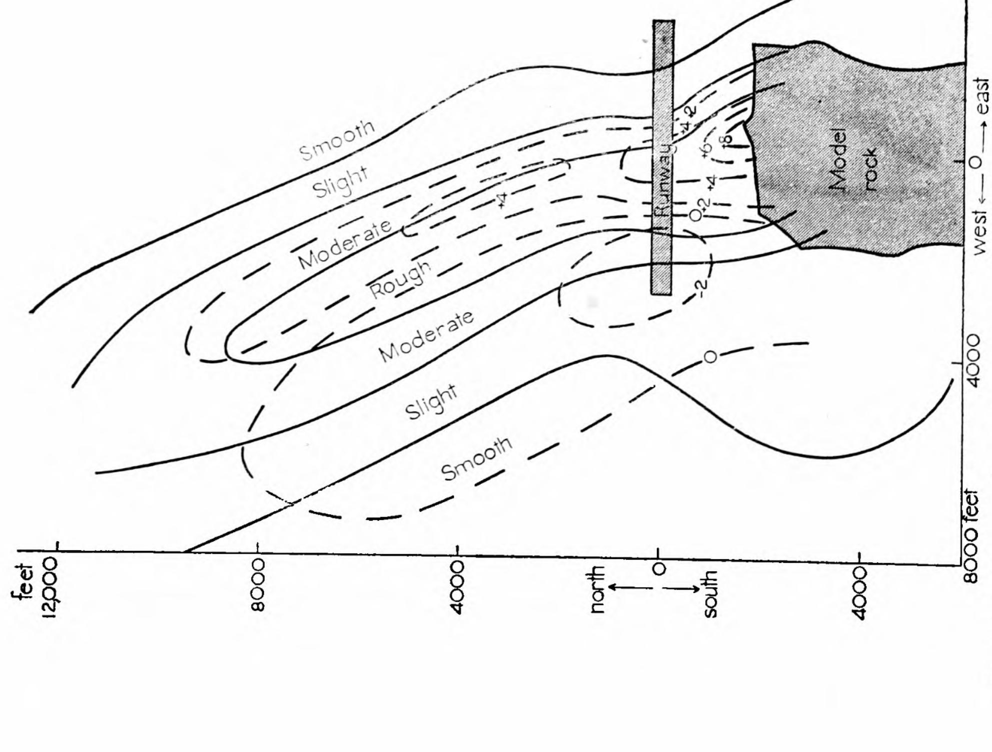


FIGURE 5. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal-height 500 feet, wind 150°.

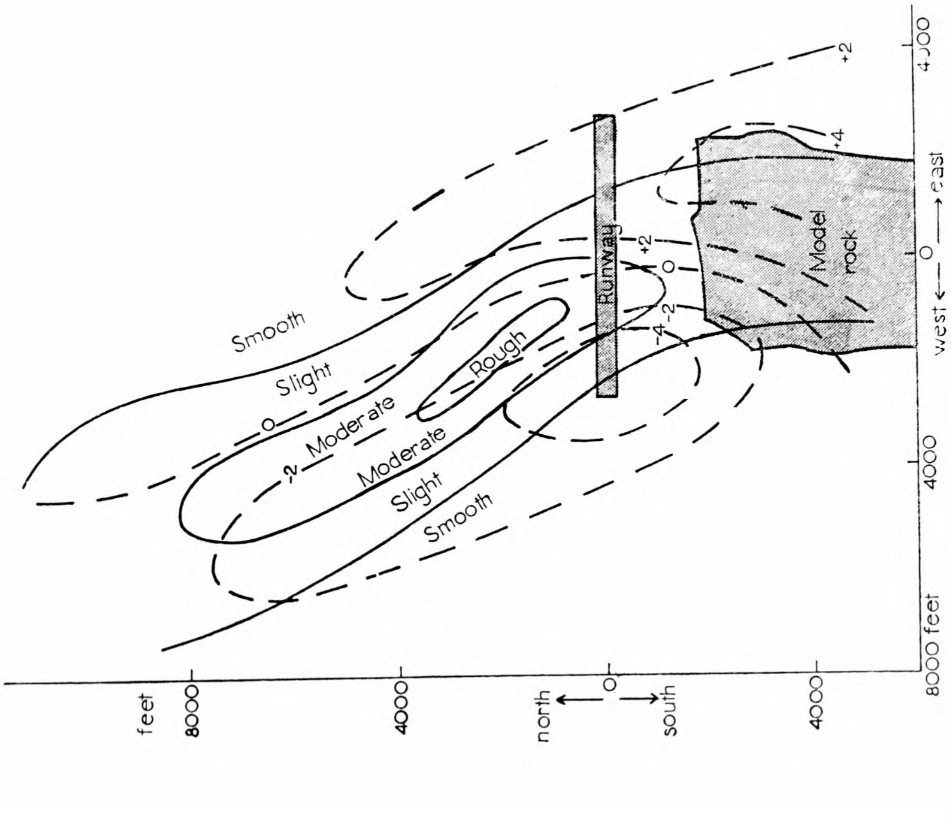


FIGURE 7. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal-height 2500 feet, wind 150°.

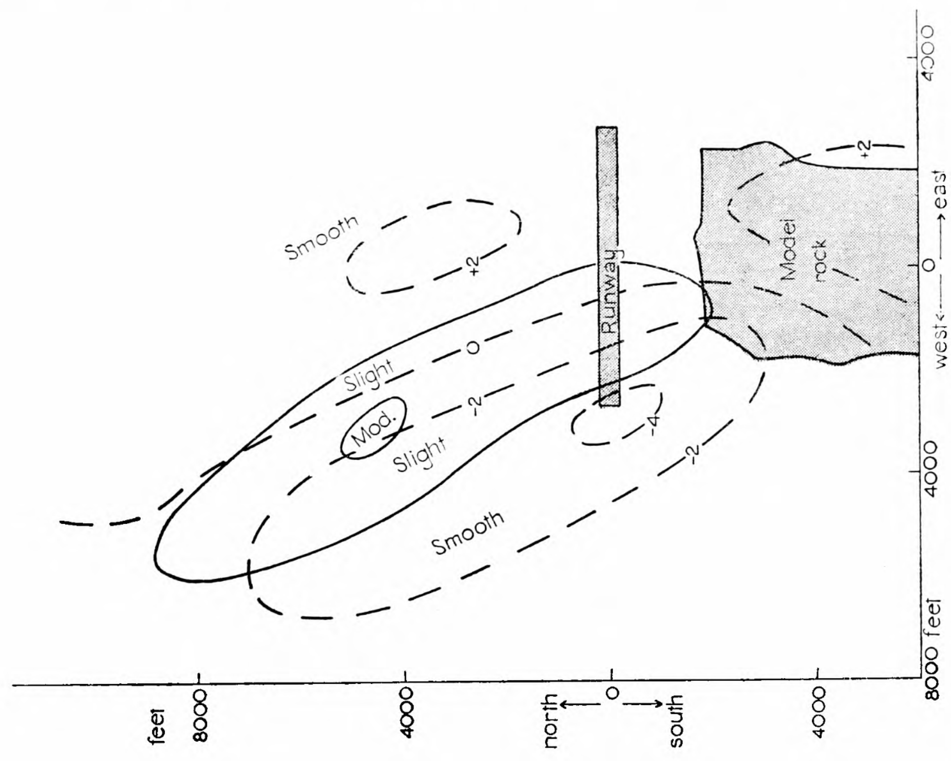


FIGURE 8. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal-height 3500 feet, wind 150°.

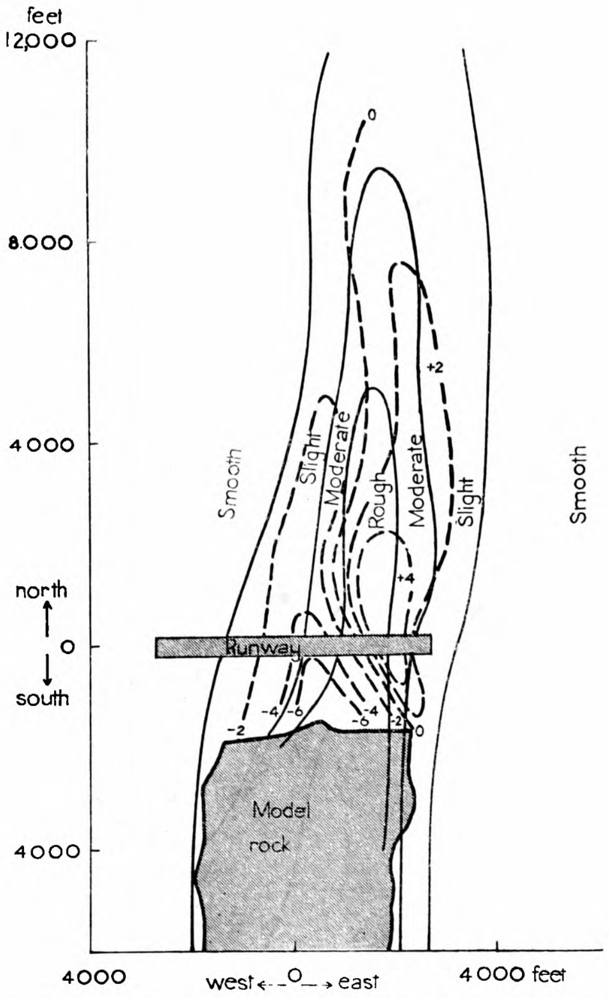


FIGURE 9. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal–height 500 feet, wind 180°.

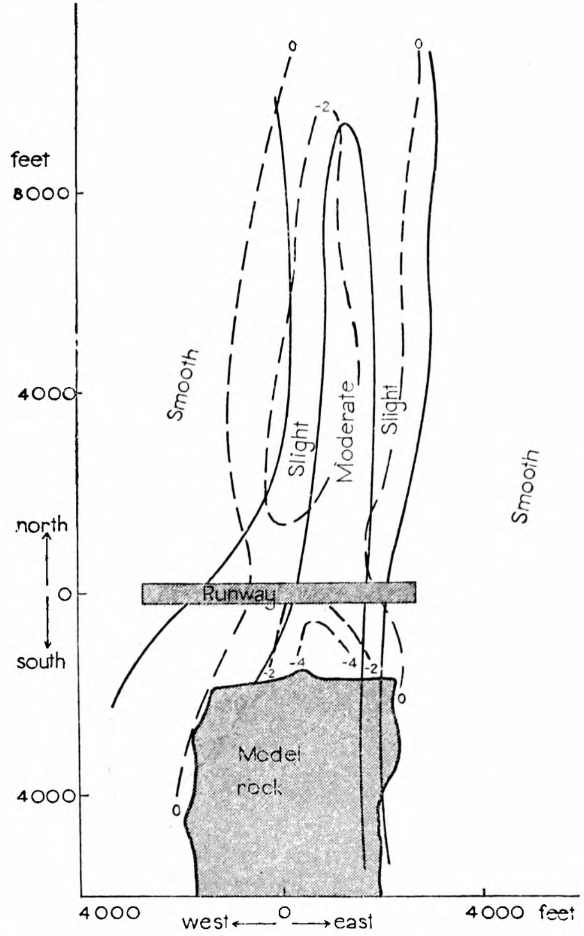


FIGURE 10. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal–height 1500 feet, wind 180°.

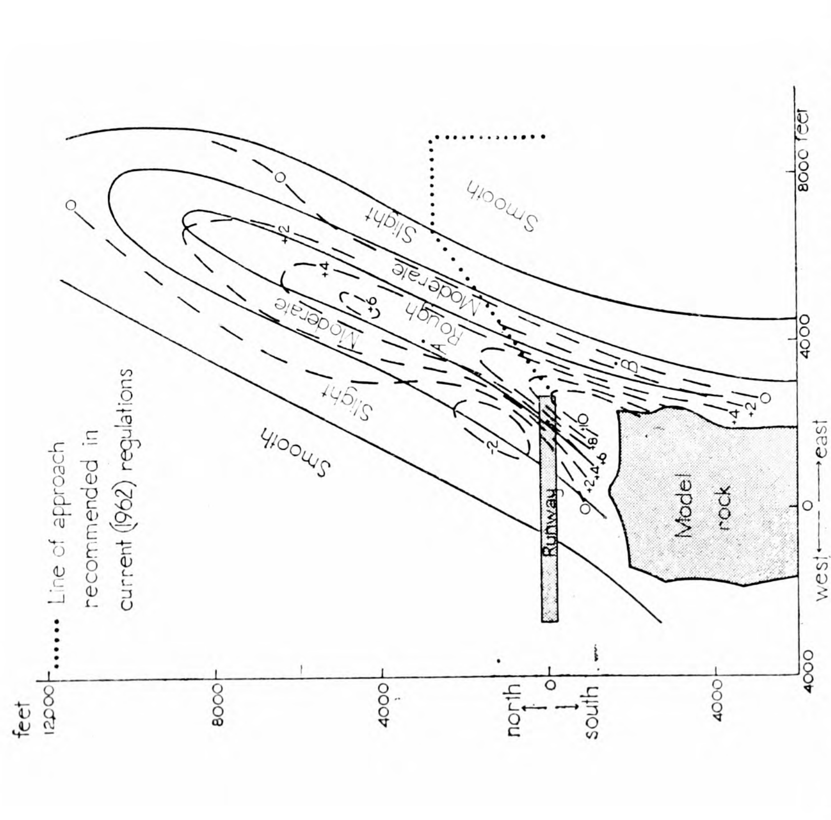


FIGURE 11. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal-height 500 feet, wind 210°.

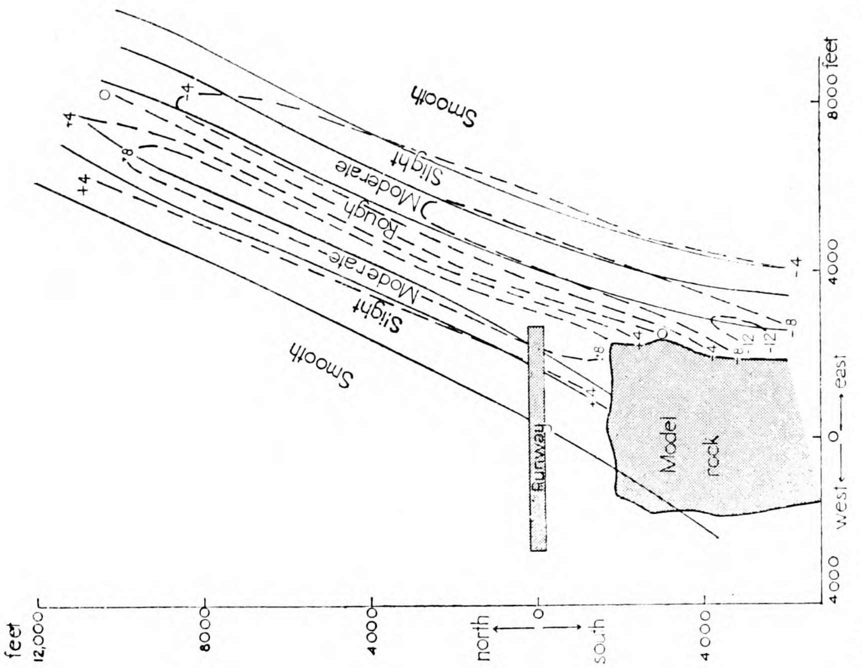


FIGURE 12. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal-height 1500 feet, wind 210°.

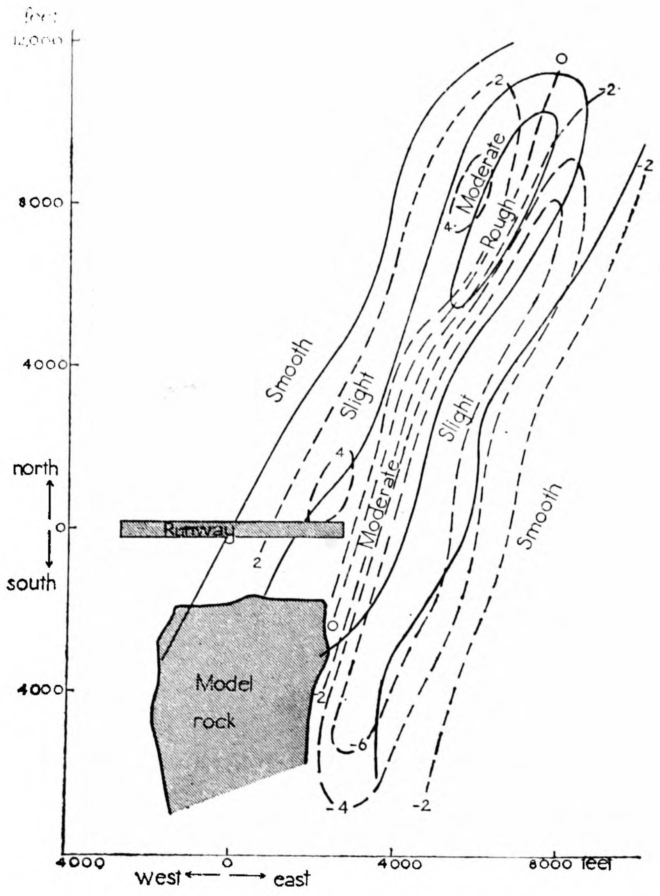


FIGURE 13. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal–height 2500 feet, wind 210°.

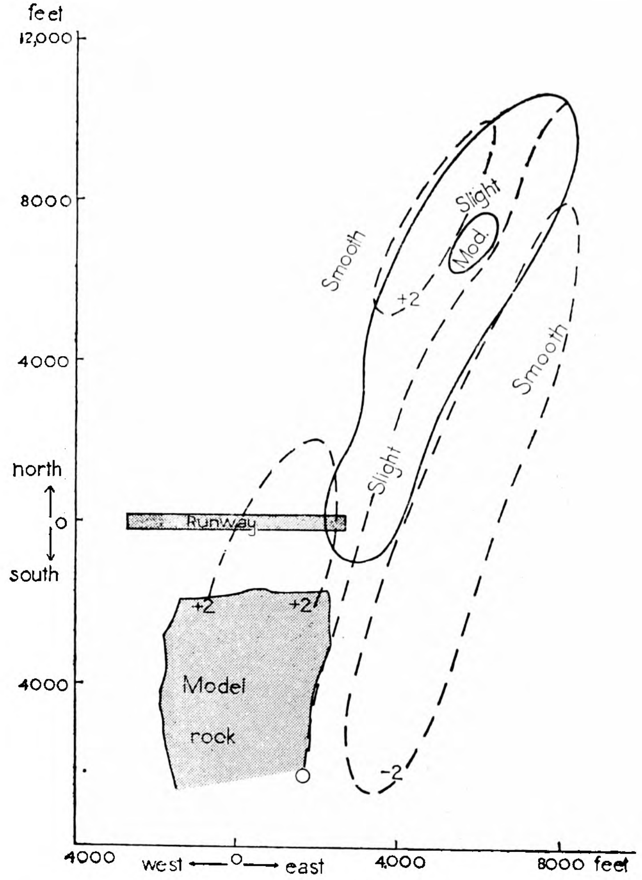


FIGURE 14. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal–height 3500 feet, wind 210°.

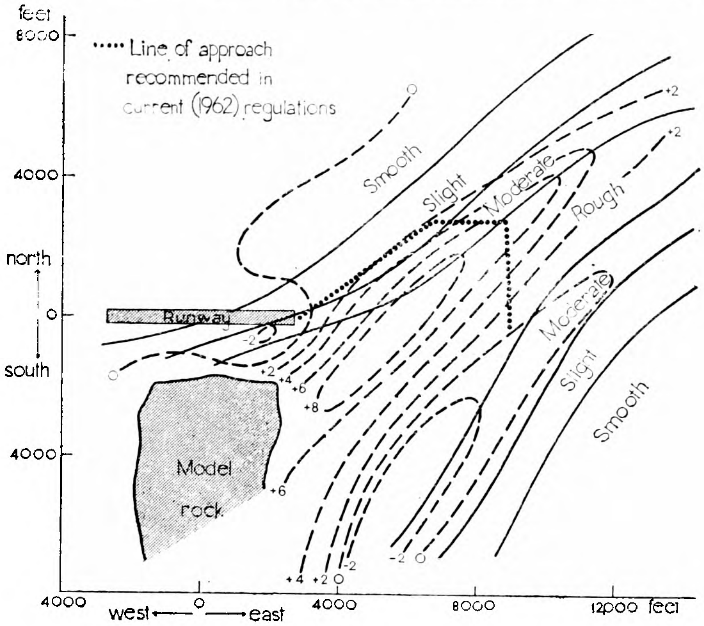


FIGURE 15. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal–height 500 feet, wind 240°.

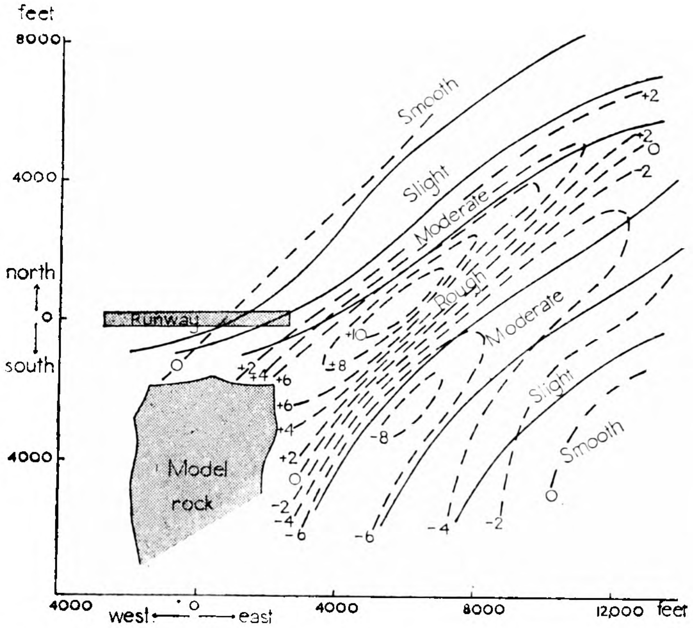


FIGURE 16. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal–height 1500 feet, wind 240°.

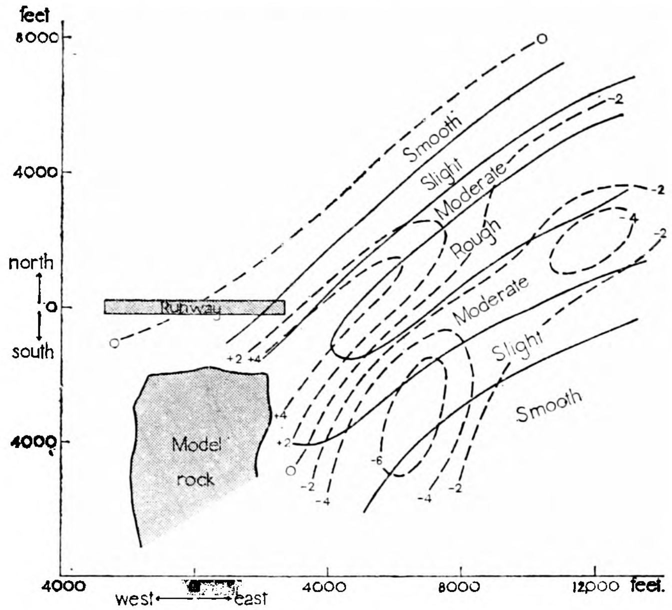


FIGURE 17. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal–height 2500 feet, wind 240°.

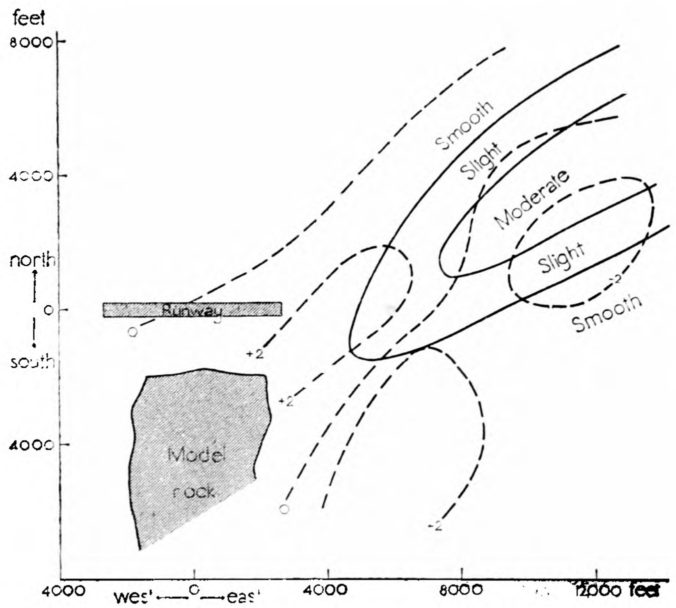


FIGURE 18. Zones of turbulence (intensity shown) and departure of mean airflow from horizontal–height 3500 feet, wind 240°.

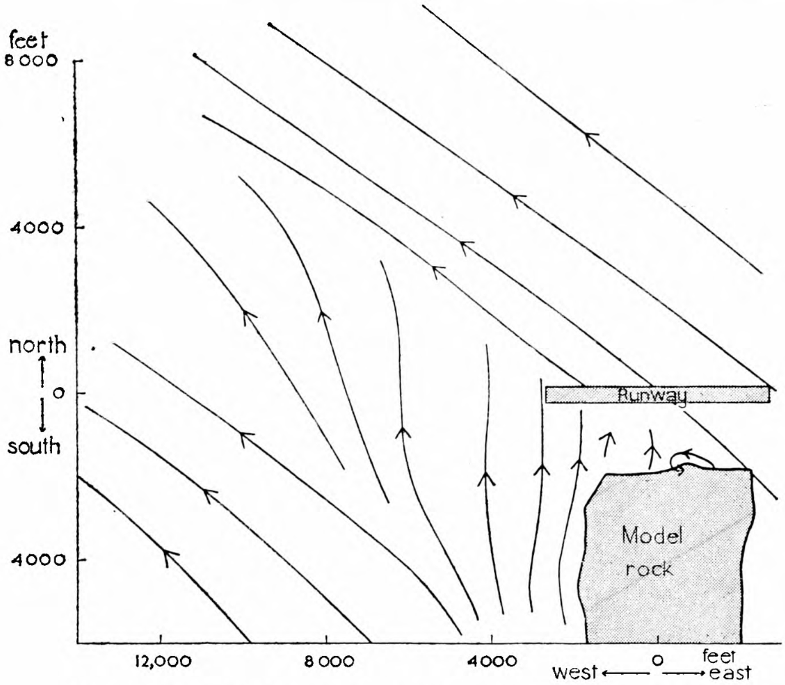


FIGURE 19. Simplified diagram of flow at 500 feet, wind 120°.

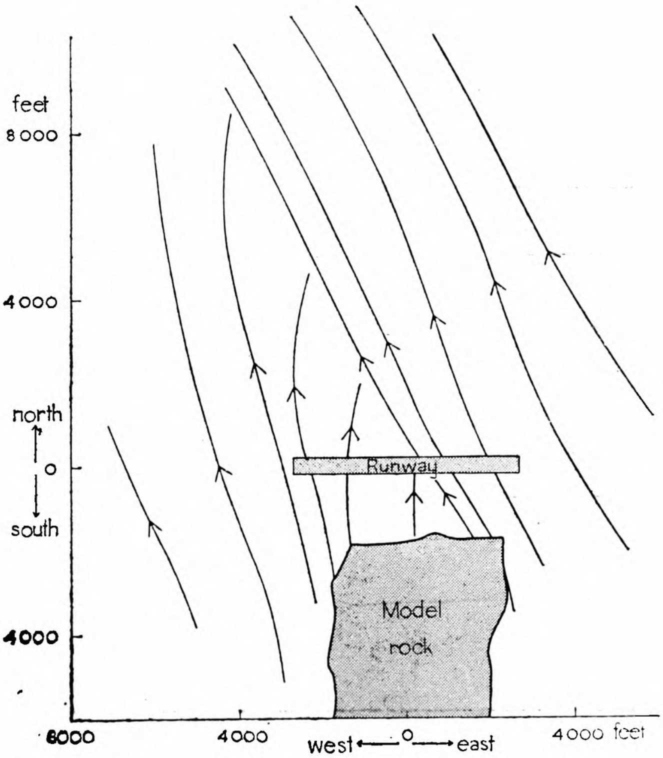


FIGURE 20. Simplified diagram of flow at 500 feet, wind 150°.

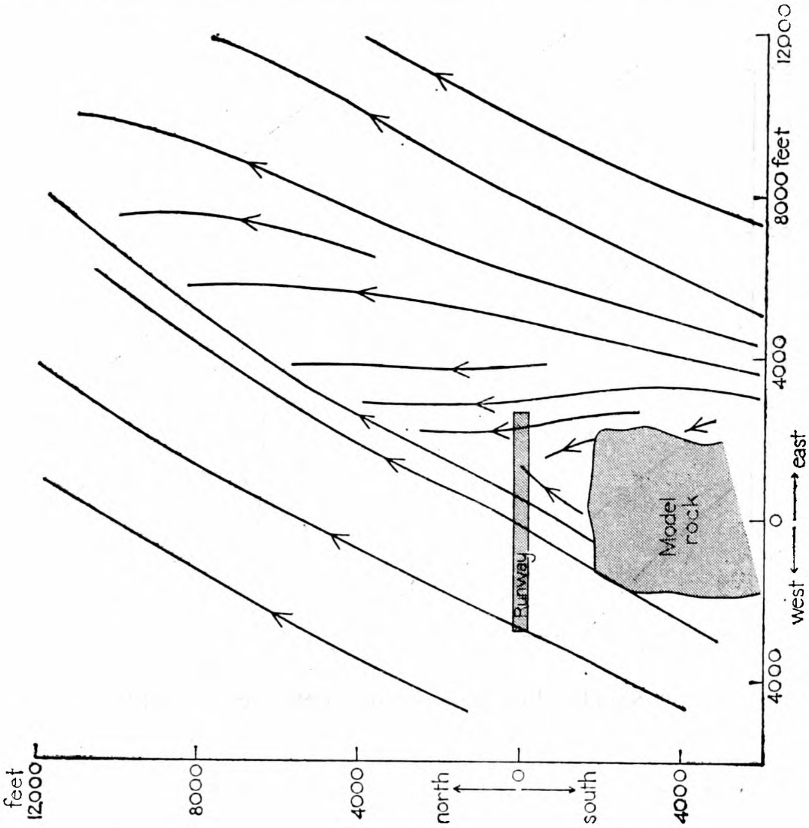


FIGURE 22. Simplified diagram of flow at 500 feet, wind 210°.

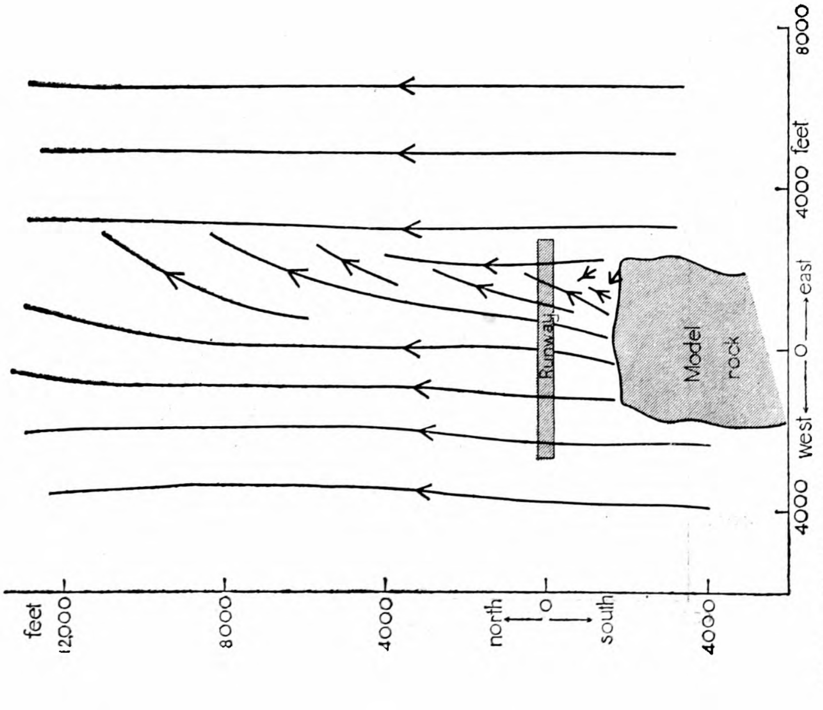


FIGURE 21. Simplified diagram of flow at 500 feet, wind 180°.

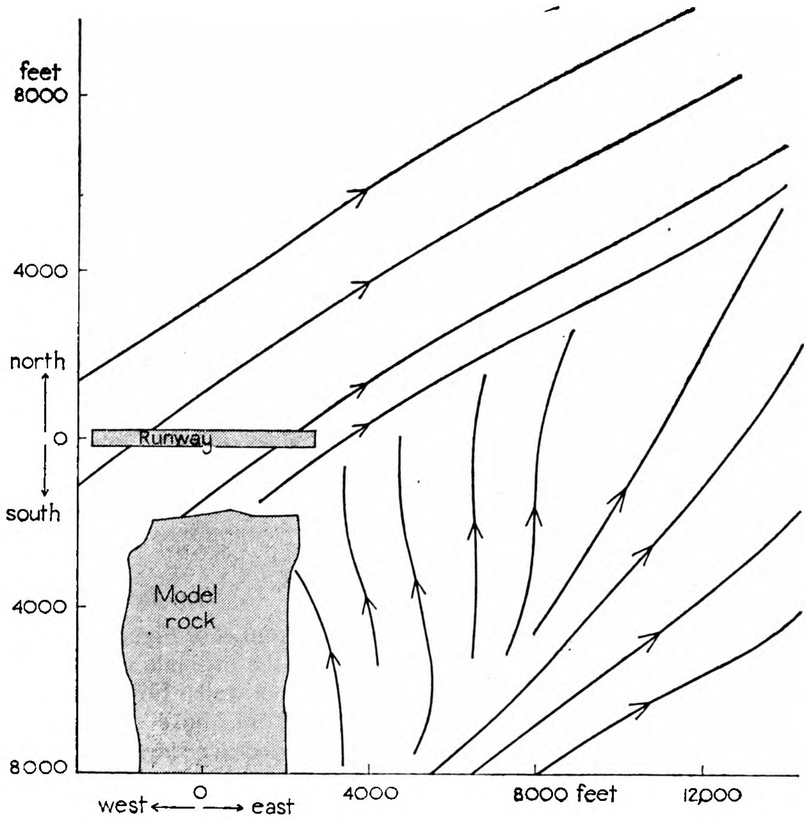


FIGURE 23. Simplified diagram of flow at 500 feet, wind 240°.

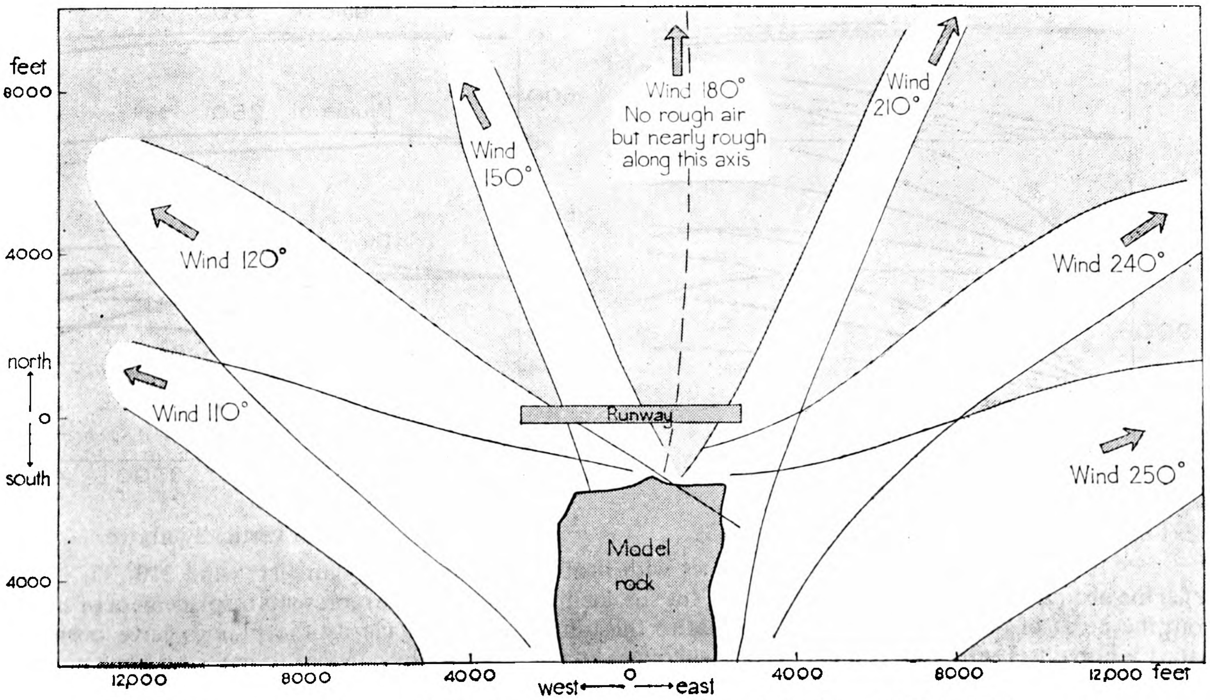
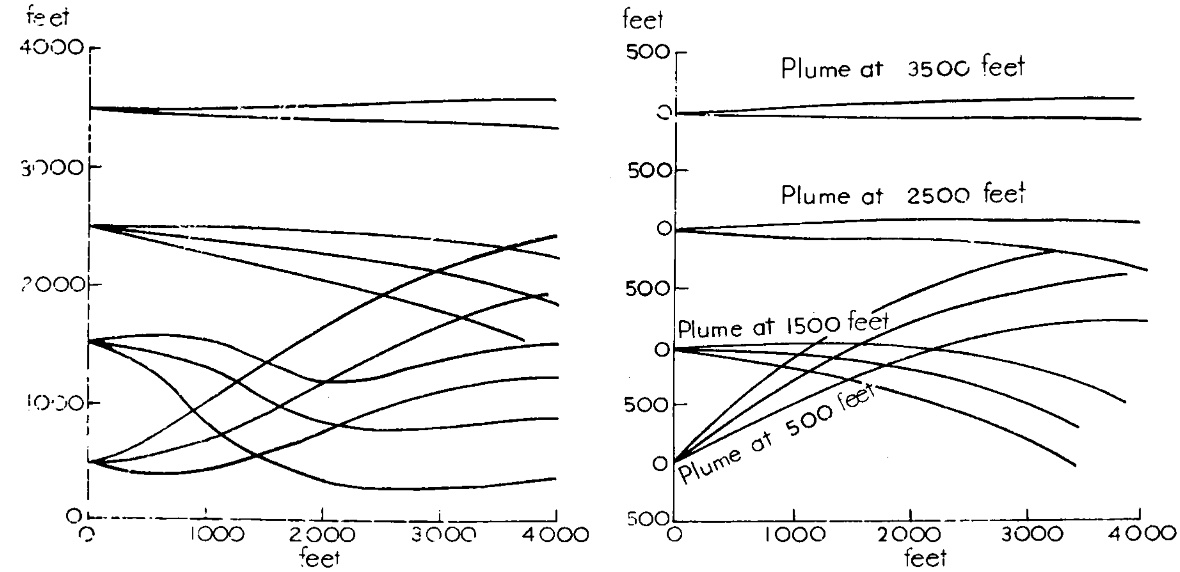
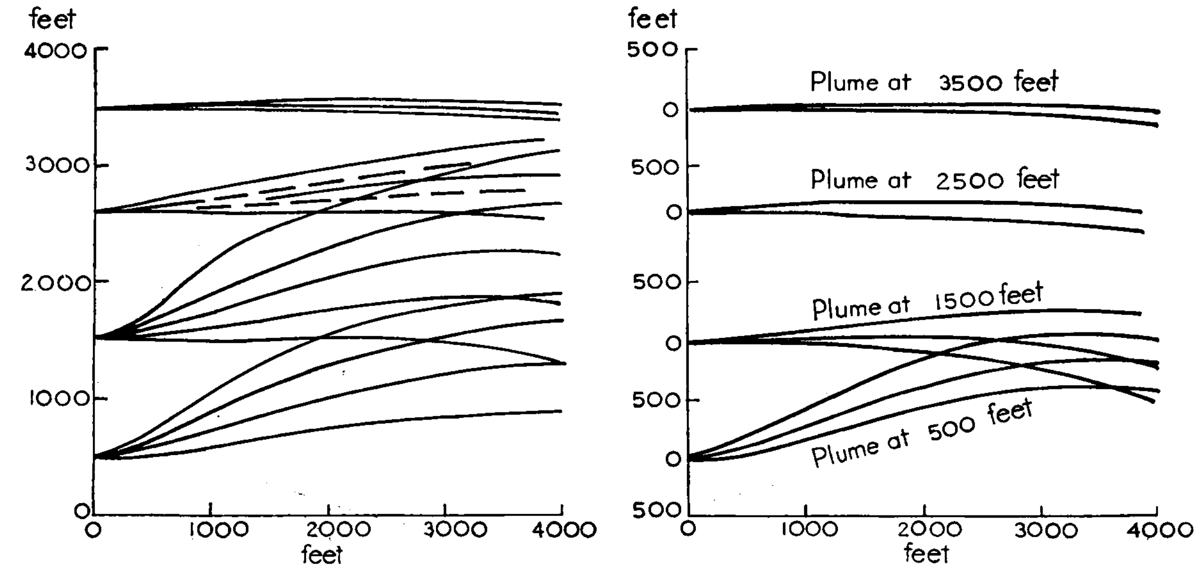


FIGURE 24. Areas of rough air at 1500 feet for winds from 110° to 250°.



(*a*) View of plumes looked at horizontally. (*b*) View from vertically above.

FIGURE 25. Sketch of smoke plumes with probes at point *A* of Figure 11, wind 210°.
In (*a*) the ordinate represents the true height of the smoke. In (*b*) the ordinate represents displacement of the smoke from the point of origin in a direction normal to the tunnel walls. For clarity the plumes have been displaced relative to each other though in fact when viewed from above they appear to have the same point of origin. Deviations to left and right of the prevailing wind are shown by departures upwards and downwards from the horizontal.



(*a*) View of plumes looked at horizontally. (*b*) View from vertically above.

FIGURE 26. Sketch of smoke plumes with probes at point *B* of Figure 11, wind 210°.
In (*a*) the ordinate represents the true height of the smoke. In (*b*) the ordinate represents displacement of smoke from the point of origin in a direction normal to the tunnel walls. For clarity the plumes have been displaced relative to each other though in fact when viewed from above they appear to have the same point of origin. Deviations to left and right of the prevailing wind are shown by departures upwards and downwards from the horizontal, respectively.

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