A NOTE ON MESO-SCALE BARRIERS TO SURFACE AIRFLOW

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The writer first encountered the problem of anomalous winds near steeply sloping terrain soon after the Arctic Forecast Team went into operation at Edmonton in 1950. At several of the stations within our analysis area, the usual relationships between surface and gradient-level winds did not appear to hold very well. From study of thousands of surface reports and wind soundings, it was evident that although the deflection angle averaged about 25°, which is normal, the ratio of surface to gradient speed tended to vary with the direction of flow. For example, at Resolute, with SW flow the ratio was usually less than 0.4, but with flow with an ENE component, the ratio was frequently greater than unity, and sometimes as high as 2.0. That station is on the south coast of Cornwallis Island, which is roughly 80 kilometers in diameter, with interior elevations around 250 meters. At that time we were aware of the diagram on page 78 in Lamb's treatise, and of the promontory effect as discussed on page 240 in the Haurwitz textbook. However, we failed to recognize the significance to our problem of an introductory remark in Queney (1948) about the "cyclonic deviation of the wind flowing against a steep mountain range...."

The data on the directions of strong winds suggested the rule that they tended to be anticyclonic around islands and cyclonic around bays and straits. A similar rule appeared to be applicable to water motions around southern Greenland, Baffin Bay, and Hudson's Strait. This was taken as confirmation of our rule for wind behavior on the assumption that water moves mainly in response to wind stress.

In 1954, when we were given the task of selecting runway orientations for the original 41 Distant Early Warning sites, without the benefit of climatological data except for Cambridge Bay, that rule was used as a major consideration. The direction of strong winds predicted for Hall Beach was NNW, for Longstaff Bluff, on the east side of Foxe Basin, ESE, and for Cape Dyer, NW. These forecasts have verified very well.

Later, it was learned from experience and compilations of data that the rule could not be used when the lapse rate was neutral or nearly neutral. In such cases, the behavior was close to normal.

The exchange of correspondence between Sheppard (1956) and Scorer (1957) provided the first clue on where to look for an explanation. Sheppard asked how a surface parcel could climb over a mountain, considering that its supply of kinetic energy could easily be exhausted by work against buoyancy before reaching the level of the crest. In reply, Scorer pointed out that it could turn to the left in front of the barrier and gain the energy required from work done during the motion across the isobars toward lower pressures.

The following is a simplified version of Sheppard's derivation. Neglecting water vapor and surface friction, the energy per unit mass expended during the climb may be obtained from the relationship, $dw/dt = -s^2z$, where w is the vertical velocity, z, the departure from the level of rest, $s^2 = g(\partial\theta/\partial z)/\theta$, g, the acceleration of gravity, and θ, the potential temperature. Integrating, $\Delta(w^2/2) = s^2z^2/2$. If the source of energy for the climb is the kinetic energy of the undisturbed flow, $U^2/2$, the level of exhaustion is given by $z = U/s$.

Identifying U as the geostrophic wind, and taking surface friction into account, the level of exhaustion for a surface parcel is roughly 0.6 U/s. For an isothermal condition, $1/s$ has a value of about 50 seconds, and for $U = 8$ meters per second, to represent mean geostrophic wind speeds, the exhaustion level is about 240 meters.

The change of kinetic energy resulting from cross-isobar motion may be described in the form, $d(V^2/2)/dy = (u/v)du/dt + dv/dt$, where $V^2 = u^2 + v^2$. Using the equations for simple horizontal motion, $du/dt = fv$ and $dv/dt = f(U - u)$, where f is the Coriolis parameter, $\Delta(V^2/2) = fU\Delta y$. Neglecting friction so that $V = U$ upstream, exhaustion occurs with a displacement to the right of $U/2f$, and $V^2/2$ is doubled by an equivalent departure to the left. With respect to a parcel that is headed toward the center of the barrier, the width that is significant with regard to exhaustion at the right side is U/f. Taking surface friction into account, the barrier width required for stoppage on the right is about 0.36 U/f. As $1/f$ is about 3 hours, with $U = 8$ mps, 0.36 U/f is roughly 30 kilometers.

If a 10% reduction of speed in front of the barrier is regarded as a threshold for a detectable effect, it may be seen that the corresponding dimensions are $1.0 - (0.9)^2 = 0.19$ times those required for stoppage.

These two parameters, U/s and U/f, first appeared in the literature, as a pair, in papers on lee-wave theory. A convenient reference is Corby (1954). It may be seen that both are prominent in the basic equation on page 497. Figure 3 in Queney (1948) may be regarded as an illustration of how they may combine to influence the pattern of flow over a meso-scale barrier.

Also, they may be considered in relation to the Froude (F) and Rossby (Ro) Numbers, as discussed on page 272 of Hess (1959). In the present context, with buoyancy as the gravitational force, $F = U^2/h^2s^2$, where h is the barrier height. Neglecting surface friction, with $F \gg 1$, the incident flow goes directly over the barrier, and with $F \leqslant 1$, it is forced to detour horizontally. The effect of the barrier becomes detectable with $F = 25$ and increases with F decreasing toward unity.

Similarly, Ro, may be defined by $Ro = U/bf$, where b is the barrier width. With $F \leqslant 1$, and $Ro \gg 1$, the incident flow is split equally in front of the barrier, but if $Ro \leqslant 1$, practically all of it detours around to the left. The effect of the barrier is detectable with $Ro = 5$, and it increases as Ro decreases toward unity.

In conclusion, although our homely rule-of-thumb has been useful operationally, it seems evident that the parameters, U/s and U/f, as a pair, can be used to advantage in dealing with the problem of airflow near meso-scale barriers.

References

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