Figure 76. Schlieren picture of waves generated in stratified fluid of uniform Von Kármán–Brunt frequency $N$ by oscillation of a horizontal cylinder at frequency 0.75$N$. Note that surfaces of constant phase stretch out radially from the source. [Photograph by D. A. Moxey.]

(a) Figure 77. Schlieren picture of waves generated by a brief horizontal displacement of a circular cylinder (a) after 10 seconds, (b) after 25 seconds. Note that the angle between crests decreases with time and is greatest, at any one time, for crests nearest to the vertical. [Photograph by T. N. Stevenson.]
(2.73) \[ \frac{U}{m} \frac{k}{m^2} \] and \[ \frac{U}{m^2} \]

The ratio of these two expressions is the slope along which a packet of waves produced at the mountain would propagate

(2.74) \[ \text{slope} = \frac{m}{k} \]

and using \( m = (l^2 - k^2)^{1/2} \) this is exactly what was derived using the method of stationary phase (2.62). The purpose of the preceding analysis was to give a physical interpretation to the train by nearly periodic waves found aloft (Fig. 5). It is appropriate to consider these as a “dispersive tail” of nonhydrostatic waves with \( k \) less than, but not much less than \( l \). If the mountain is too broad and smooth to create any of these shorter

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Fig. 5. The flow over a ridge of intermediate width \((aI = 1)\) where the buoyancy forces are important, but not so dominant that the flow is hydrostatic. The dispersive character of the nonhydrostatic waves \((k \text{ less than, but not much less than } N/L)\) is evident as they trail behind the ridge. Parameters are as in Fig. 3 except \( a = 1 \) km. (From Queney, 1948.)
Fig. 1. Mountain topography in the vicinity of Boulder, Colo. Altitudes are in feet (10,000 ft = 3048 m).
Fig. 2. Analysis of (a) potential temperature and (b) u-component speed from aircraft flight data and sondes.
Fig. 3. Vertical cross section of the simulated potential temperature after 3 h for (a) ARPS, (b) COAMPS, (c) CUMM, (d) DK83, (e) EULAG, (f) MESO-NH, (g) MM5, (h) NTU/Purdue, (i) RAMS, (j) RIMS, and (k) UCLA models. The contour interval is 8 K.
Defining characteristics of the QBO are:
1) The wind regimes propagate down as time progresses.
2) They move downwards at roughly 1km/month and decrease in magnitude as the height decreases.
3) The period of the oscillation is 20 to 36 months with a mean of around 28 months.
4) They start at 10mb and descend to 100mb.
5) The maximum amplitude of 40 to 50m/s is seen at 20mb.
6) Easterlies are generally stronger than westerlies.
7) Westerly winds last longer than easterly winds at higher levels while the converse is true at lower levels.
8) The westerlies move down faster than the easterlies as shown by the steepness of the zero line.
9) The transition between westerly and easterly regimes is often delayed between 30 and 50mb.
10) There is considerable variability of the QBO in period and amplitude.
Zonal mean wind at 10 mb
April 1993 zonal mean cross section
Plate 1. (top) Time-height section of the monthly-mean zonal wind component (m s\(^{-1}\)), with the seasonal cycle removed, for 1964–1990. Below 31 km, zonal winds are from the G. A. B. O., Rev. Geophys., 39, 179–239.

Plate 2. Dynamical overview of the QBO during northern winter. The propagation of various tropical waves is depicted by orange arrows, with the QBO driven by upward propagating gravity, inertia-gravity, Kelvin, and Rossby-gravity waves. The propagation of planetary-scale waves (purple arrows) is shown at middle to high latitudes. Black contours indicate the difference in zonal-mean zonal winds between easterly and westerly phases of the QBO, where the QBO phase is defined by the 40-hPa equatorial wind. Easterly anomalies are light blue, and westerly anomalies are pink. In the tropics the contours are similar to the observed wind values when the QBO is easterly. The mesospheric QBO (MQBO) is shown above ~80 km, while wind contours between ~50 and 80 km are dashed due to observational uncertainty.
Fig. 2. Theoretical results. Frequency ($\omega$) and diffusivity ($\nu$) are plotted as functions of the east-west wavenumber $k$. The north-south wavenumber is assumed equal to $k$. In regions on the hatched side of solid lines no vertical propagation is possible. The long-dashed lines show solutions with the observed vertical wavenumber; from top to bottom they represent acoustic, inertia-gravity, and Rossby waves. The short-dashed lines are diffusivities calculated as explained in the text. They correspond, from top to bottom, to the same three solutions. The dash-dot line shows the kinematic viscosity of $\mathrm{H}_2$ as a function of number density ($n$) plotted across the top.