atmospheric gravity waves
and the energy of the
downstream sides of mountains. Recently, Lilly (1972) proposed that the
vertical energy transporting properties of mountain lee
waves might account for 2 to 3 m sec\(^{-1}\) of the 5 m sec\(^{-1}\) discrepancy between the observed mean and computed
speed of the jet stream.

Prior to Lilly's investigation, Gossard (1972) recorded
large gravity waves localized on the inversion surface that
classifies the California coast. Recorded pressure
amplitudes were about 0.2 to 0.3 mb. Calculations of
vertical energy flux for these waves based on a simple
two layer model of the atmosphere gave values as high
as 1000 erg cm\(^{-2}\) sec\(^{-1}\). This energy transfer rate is about
one-fifth that of the surface drag on the westerlies. Gos-
sard was concerned with the possibility of transmission of energy from the troposphere to the ionosphere by
means of gravity waves. More recently, Reed and Hardy
(1972) showed radar reconstruction of internal gravity
waves at several levels in the upper troposphere. These
waves had a double amplitude of approximately 0.6 km,
a wavelength \(2\pi/K = 17\) km, and a phase speed, \(c \approx 67\)
m sec\(^{-1}\). The phases tilted strongly (slope, \(r \approx -1\)) up-
stream (or westward) with elevation, thus implying a
considerable downward transport of westerly momentum.

An estimate for the magnitude of this transport can
be obtained in the following manner. The vertical flux of momentum due to waves is given by \(\rho \overline{w' w'}\) where \(\rho\) is
the density, \(w'\) is the perturbation horizontal velocity
(west to east), \(w'\) is the perturbation vertical velocity and
the overbar indicates an average. Assuming that
\(w' = f(z) \sin (x \cdot t - ct)\) for the eastward coordinate and \(z\) the vertical, the momentum transport is then given by

\[
\rho \overline{w' w'} = \rho \frac{f'(z)}{2}.
\]

From the kinematic relationship between wave displace-
ment \(\eta\), and vertical velocity we find that

\[
\eta \approx \frac{1}{(U-c)k} f(z).
\]

With an average velocity in the layer of \(U \approx 59\) m sec\(^{-1}\) we obtain a vertical momentum flux of

\[
\rho \overline{w' w'} \approx -1.6 \text{ dynes cm}^{-2}.
\]
FIG. 1. Comparison of Friez daily microbarogram of 22 December 1972 (top) with gravity wave records (bottom) from the Lamont quadrupartite microbarovariograph array. The bracketed portion of the Friez record corresponds to the larger time-scale gravity wave records on which one-minute time blips are shown. Many waves exceed the chart scale. Maximum amplitudes on both records reach at least 0.4 mb. (The second channel was inoperative.)

The total momentum in a one square centimeter column of the atmosphere is approximately $2 \times 10^6 \text{ gm sec}^{-1} \text{ cm}^{-1}$ assuming an average winter zonal wind of 20 m sec$^{-1}$. If the above transport acted continuously at the same rate it would drain all momentum from the westerlies in about 14.5 days. Using a similar calculation, Widger (1949) showed that surface friction and mountain torques combined would remove all westerly momentum in about 10 days. Because such large gravity waves as those reported above are not continuously present in the belt of westerlies, the integrated effect of the transports due to gravity waves will of course be smaller. Nevertheless, the above-mentioned case reveals the fact that traveling gravity waves may well account for a significant fraction of the momentum drained from the westerlies.

These works led us to invoke traveling gravity waves also as an important means of transferring momentum and kinetic energy vertically from the jet stream in view of their very common and widespread occurrence. We are attacking the problem in a two-fold manner. First it is necessary to establish unambiguously the connection between the upper westerlies and traveling gravity
waves. The second part of the study, once the connection is established, will be to obtain measurements of the vertical energy and momentum flux at as many elevations as possible and infer the flux along the vertical by means of an appropriate model.

We have already begun preliminary work in this investigation and can indicate initial progress.

Several prior studies have been made that show correlation between surface pressure perturbations and the winds aloft. Flauraud et al. (1954) and Claerbout (1967) concentrated on waves between about 5 and 30 min and showed that good coherence prevailed over arrays of the order of a wavelength, as with ours. Herron and Tolstoy (1969), investigated longer period perturbations between 30 and 90 min. Because these latter oscillations decorrelated over distances less than a wavelength they were not considered to be free gravity waves. Incomplete case comparison of gravity waves and synoptic features have also been made, e.g., Donn (1954), Jordan (1972). What is missing so far is a detailed comparison of waves, vertical winds and meteorology by means of a documented time series of events. An inherent difficulty has been the lack of ability to infer detailed profiles of wind aloft because of the 12-hr interval between observations and the wide separation between upper air stations. These impose particular difficulties when working with phenomena of subgrid scale size. A good case in point correlating waves and jet stream can be shown for 17-19 May 1970. In this case, as will be seen, changes in the upper air flow pattern over the station are so marked that a detailed time sequence of gravity waves and winds aloft can be closely correlated.

Fig. 2 a, b and c shows the progress of a 500-mb elongated, closed low across the northeast section of United States. Preceding the trough axis, winds are southerly with high velocity (Fig. 2a). The center of the low passed over our wave recording area at about the time of the chart in Fig. 2b. Following the center passage an abrupt wind shift to north and resumption of strong winds occurred (Fig. 2c).

During the interval of high southerly winds aloft (Fig. 2a) large amplitude traveling gravity waves (150 μbars) were recorded by our pressure sensors. As the low center crossed the area wave amplitudes dropped to a minimum and then increased rapidly again several hours later when the northerly winds set in following the passage of the center.

The gravity wave parameters of direction and amplitude are compared in detail with 500-mb wind data taken from the Northern Hemisphere upper data tabulations in Figs. 3a and 3b, respectively. The very close correspondence between wind and wave directions is seen to be quite evident in Fig. 3a. Particularly striking is the near reversal of directions of both wind and waves from southerly to northerly. In Fig. 3b, the close correspondence between wave amplitudes and wind speed at the 500-mb level is also very evident as is true of many other cases studied. Note that the 500-mb level is used here merely to provide an indication of the wind pattern aloft. No implication is intended about the precise level of wave generation which is presumably in the layer of smallest Richardson number. We
FIG. 3a. Comparison of 500-mb wind direction (broken line) with calculated gravity wave directions (circles) for 17-20 May 1970.

FIG. 3b. Comparison of 500-mb wind speed (broken line) with the pressure amplitude (solid line) of gravity waves. The curve for wind speed is based on reasonable interpolation between 12-hr observation points and the isotach pattern on available charts.

note that Claerbout (1967) showed a remarkable correlation between the velocity of gravity waves measured at the surface and the wind velocity in the region of smallest Richardson number aloft.

In order to accurately assess the energy and momentum transferring properties of the waves it is desirable to determine the average product of the horizontal and vertical components of the winds at all heights through the troposphere. Measurements of these values are hardly possible for all levels. Among the alternative approaches are: 1) the acquisition of three-dimensional wind data from wind recorders on tall structures used in conjunction with a realistic model capable of inferring energy transfer terms at all other heights through the troposphere; 2) the use of high-resolution radar, as described above.

Such a program is being initiated here at Lamont-Doherty Geological Observatory. Preliminary results based on a model by Balachandran which describe an atmosphere with as much as one hundred layers has already provided us with results showing 1) large wave amplitudes in cases with inversions and wind shear aloft and 2) vertical profiles of all perturbation quantities (including kinetic energy). This model must now be amended so as to provide vertical momentum transport terms.

Such information, taken in conjunction with the studies now underway for determining similar effects due to mountain waves, may well provide more accurate assessment of the role of the short wavelength end of the spectrum of the general circulation.

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References