SHORTER CONTRIBUTION

An observational study of lee waves using radiosonde data

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(Manuscript received September 20, 1971; revised version August 28, 1972)

1. Introduction

Corby (1957) showed that radiosonde data could be used to detect departures of the vertical velocity of the instrument, of a few m sec^{-1}, from a mean value. Occasionally marked periodic variations of the vertical velocity along the path of the balloon suggested the presence of atmospheric gravity waves, almost certainly due to orography, extending through considerable depths of the atmosphere. Corby limited his study to levels below 40 000 ft; however, on some occasions the waves which he inferred maintained considerable vertical velocities up to this level and may have extended considerably higher. In the present investigation improved British radiosonde data have been examined for indications of small-scale air motions at all levels. Some emphasis has been placed on motions in the lower stratosphere, which have considerable practical interest in view of the imminent operation of supersonic aircraft there.

2. The use of radiosonde data to detect lee waves

In present radiosounding practice the pressure measurements are automatically recorded on a paper chart (as a function of time). This improvement upon the manual records used by Corby simplifies the analysis by making departures of the vertical velocity of the radiosonde from a mean value visible as changes in the gradient of the pressure trace (the curve defined by the pressure readings). In a typical record changes in the vertical velocity of the radiosonde of about 1 m sec^{-1} or more may be inferred from an inspection of the records. The vertical velocity may be plotted as a function of time and corrected for the effect of temperature on the aneroid instrument. For the analysis of a large volume of data it was found that the period and amplitude of the waves could be satisfactorily deduced directly from the pressure trace.

The drag force of about 2.5 kg which acts on the ascending radiosonde balloon is proportional to the square of its air speed. Consequently, departures of the rate of ascent from the equilibrium value determined by the drag and the buoyancy of the balloon, are quickly eliminated and are unlikely to affect the radiosonde record. It does appear, however, that the drag force, itself, varies during a sounding, because of changes in the Reynolds number associated with changes in air density and in the size of the balloon. The drag coefficient can change rapidly enough to markedly change the slope of the pressure trace, particularly in the upper troposphere and lower stratosphere where the Reynolds number enters the critical range between 10^5 and 10^6.

The switching between the pressure, temperature, and relative humidity sensors in the radiosonde is controlled by the rotation of the windmill, which is a crude anemometer mounted in a vertical plane on the outside of the radiosonde. In certain soundings the rate of switching has been noted to increase and decrease in the same manner as the vertical velocity. It further has appeared possible to calibrate the windmill so that a useful measure of the rate of ascent of the radiosonde through the air can be obtained. Variations of the rate of ascent have been observed to occur and often have a maximum in the upper troposphere.

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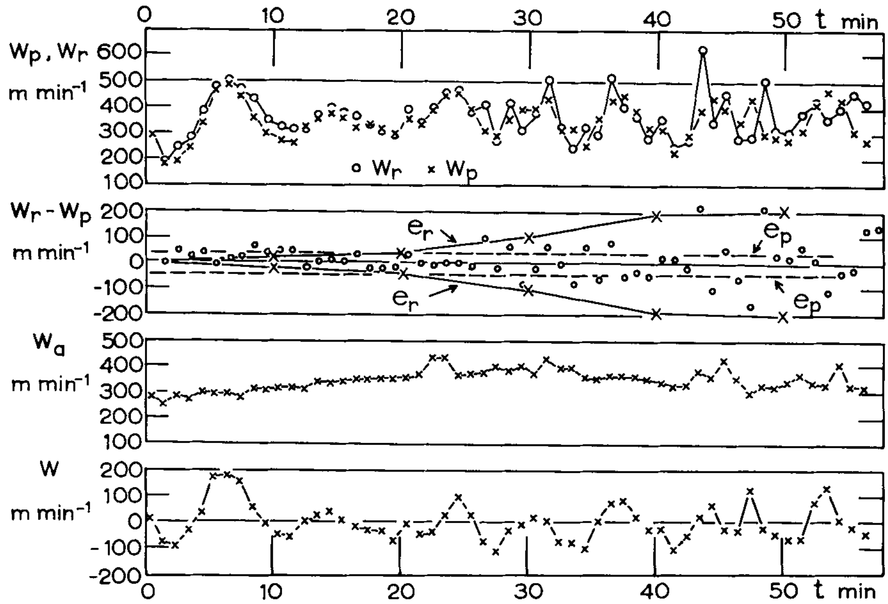

Fig. 1. Features of the vertical motion of the radiosonde launched from Shanwell at 2330 GMT on the 4 September 1966, plotted against t, the time after launch. (a) A comparison of the vertical velocity inferred from the pressure trace, w_p, and that inferred from the radar, w_r. (b) A comparison of the difference between w_p and w_r (circles), the expected maximum error in the derivation of the vertical velocity from the pressure trace, e_p (pecked line), and from the radar observations, e_r (continuous line). (c) The rate of ascent of the radiosonde through the air, w_a, derived from the rate of switching. (d) The vertical air speed, w, encountered by the radiosonde, deduced from the difference between w_p and w_a.

Rates of ascent as large as 15 m sec^{-1} have been detected and could be confused with lee waves.

The points plotted in Fig. 1 represent features of the vertical motion of the radiosonde launched from Shanwell (on the E. coast of Scotland) at about 0000 GMT on the 5 September 1966. The record was remarkable for the wavelike disturbances of the pressure trace throughout the sounding. The regular periodicity of the disturbances suggested the presence of gravity waves up to heights near 16 km.

The independent measures of vertical velocity given by the Cossor wind-finding radar and by the pressure aneroid agree satisfactorily in the period up to about 20 minutes after launch. Subsequently a small peak of ascent speed between 20 and 21 minutes appears on both records and is probably real; the next peak at 24 minutes is well defined. The minima at about 28, 34, and 42 minutes, and the peaks at about 31, 37 and 44 minutes are probably real.

The gradual deterioration after 20 minutes in the agreement between the two measures is accompanied by an increase in the scatter of vertical velocities indicated by the radar. This scatter may be attributed to errors in the indicated elevation angle, which is read only to the nearest 0.1° (the magnitude of the error in the vertical velocity which may thus be incurred is plotted as a function of time in Fig. 1b and is compared with the difference between the two measures).

Values of the rate of ascent of the radiosonde through the air estimated from the rate of switching are shown in Fig. 1c. It can be seen that none of the clearly defined wave-like disturbances of Fig. 1a is reproduced, although some irregularities are present. Nevertheless, the result of subtracting these values from the vertical velocities inferred from the pressure trace does not remove any of the wave-like character of the disturbances. The form of the variation (Fig. 1d) strongly suggests that the encountered variations are due to the passage of the balloon through lee waves.

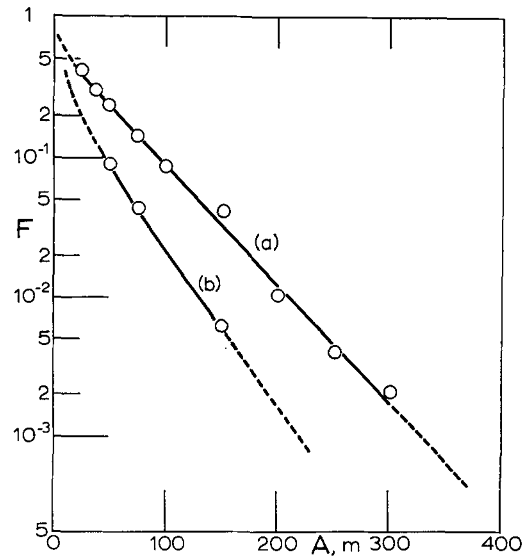

Fig. 2. The fractional frequency F of waves with maximum streamline displacements exceeding A, (*a*) at low levels (about 2 km), (*b*) in the lower stratosphere (at about 16 km), based on an analysis of 500 soundings at Shanwell in 1964.

2. Properties of lee waves

(a) *The amplitude of lee waves*

The frequency of occurrence of wave-like features on 500 Shanwell records for the year 1964 has been assessed in two parts of the radiosonde record, corresponding to heights of about 2 km and 16 km (Fig. 2). As the radiosonde may rise a few km while passing through one complete wavelength the inferred amplitude must necessarily be an average over such a depth, and lee waves confined to shallow layers may escape detection. The two heights chosen appear to be representative of the levels at which lee waves most frequently have their maximum amplitude in the troposphere and in the lower stratosphere respectively. At 16 km the sensitivity of the radiosonde is only adequate to detect waves of amplitude 50 m or greater: at 2 km waves with vertical displacements of 25 m or more are detectable.

Fig. 2 shows that the amplitude exceeds 100 m for about 10 % of the time at 2 km and for about 2 % at 16 km. Most systems of waves have a minimum amplitude at an intermediate height near the tropopause; Corby's (1957) data on the height of the maximum amplitude indicate the behaviour of the amplitude up to about 13 km.

The seasonal frequencies of pronounced waves at Shanwell have been estimated for the period between 1964 and 1967. Waves occurred most frequently in the winter months, both in the troposphere and in the stratosphere. During the summer the frequency in the stratosphere decreased more than in the troposphere; this suggests that the strong westerly winds in the stratosphere during the winter favour lee waves there. The seasonal frequency varied markedly from year to year.

(b) *The wave period*

A most distinctive feature of wave-like disturbances is the regularity of the time interval between successive crests or troughs on the pressure trace. The sounding in Fig. 1 illustrates this, although the time taken for the radiosonde to pass from one region of upward air motion to the next tends to decrease a little with height; thus the interval between the first two updraught maxima is 9 minutes, and that between the two downdraught maxima is 8 minutes, while at high levels it is about 7 minutes. This period corresponds to the wave period, if the wave crests and troughs lie in vertical planes and if the period remains constant in the layer under consideration.

The frequency of occurrence of individual periods (to the nearest whole minute) from Fig. 2 are shown in histogram form in Fig. 3. The data at 2 km contain a considerable proportion of waves of amplitude between 25 and 50 m, not represented in the data at 16 km.

The most frequent periods at 2 km lie between 6 and 10 minutes and correspond to typical values of the Brunt–Vaisala period (the period of a simple inertial oscillation of a parcel given a small vertical displacement). The high correlation between the wavelength and the mean wind speed observed by Corby (1957) shows that the periods in his data also cluster about 8 minutes, with a maximum value of 10 minutes. The most frequent period at 16 km is 5 minutes which corresponds to the Brunt–Vaisala frequency when the stratification is approximately isothermal.

(c) *The lee wavelength*

If the lee waves are further assumed to be stationary with respect to the ground and to

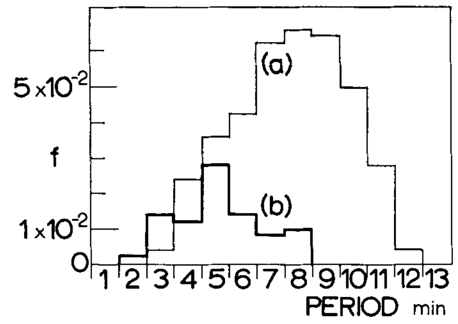

Fig. 3. The fractional frequency f of waves of a given period (expressed to the nearest whole minute), (*a*) at low levels (about 2 km), (*b*) in the stratosphere (at about 16 km), based on an analysis of 500 soundings at Shanwell in 1964.

lie across the wind, multiplication of the wave period by the wind speed in the layer in which the period is measured, yields the wavelength. Values are much more variable than the corresponding wave periods, changing not only from sounding to sounding but also from height to height. On night soundings during January 1964 wavelengths inferred from radiosonde records were fairly evenly distributed between 3 and 25 km in the troposphere. Values in the stratosphere ranged from 3 to 14 km and in particular cases were often shorter than those in the lower troposphere. The most pronounced waves in the lower stratosphere, however, have wavelengths about 10 km and have similar wavelengths in the lower troposphere.

4. Conclusions

The lee waves inferred by inspection of the radiosonde records from Shanwell (E. Scotland) for 1964 have streamline displacements exceeding 100 m about 10 % of the time at 2 km and about 2 % of the time at 16 km. The frequency of lee waves is greatest during the winter months; during the summer the frequency in the lower stratosphere decreases more markedly than in the troposphere. Under certain assumptions the wave periods are found to correspond to typical values of the Brunt–Vaisala period, and the smaller periods occurring in the stratosphere imply that rather short wavelengths of only a few km may occur there.

REFERENCES

Corby, G. A. 1957. A preliminary study of atmospheric waves using radiosonde data. *Quart. J. R. Met. Soc. 83*, 49–60.