Winds and Wave Motions to 110 km at Mid-Latitudes. IV. Coupling Between Internal Gravity Waves and the Mean Flow

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ABSTRACT

The results of radiowave partial reflection drift (wind) measurements from 60–110 km, for the years 1973–74, at Saskatoon, Canada (52°N, 107°W), are presented. Intensive soundings (12 profiles per hour) have provided hourly, weekly and monthly profiles for the prevailing winds and also for the amplitudes of internal gravity (I.G.) waves ($\tau \approx 60$ min).

A relationship between the heights of reversals of the mean flow and of maxima in the I. G. wave amplitude profiles is demonstrated for 1973 and 1974. Hourly changes in the flow are also shown to be consistent with the effects of longer period ($\tau \approx 120$ min) I. G. waves and/or momentum deposition by I. G. waves ($\tau \lesssim 60$ min). It is shown that gravity waves are a major contribution to the dynamical and energetic balance of the lower thermosphere (80–110 km).

1. Introduction

This paper presents results from a continuing program of partial reflection radiowave drift (wind) measurements from 60 km up to and including the ionospheric E region, for a location at 52°N, 107°W (Park Observatory near Saskatoon, Canada). In Paper I of this series (Manson *et al.*, 1974), data from closely spaced atmospheric soundings (12 per hour) for the period August 1972–September 1973 were presented. It was shown that the median of the wind profiles for a given hour could be identified mainly as the prevailing wind, or "background flow"; and the irregular components from each profile as internal atmospheric gravity (I.G.) waves.

In this paper comparisons are made between the data of 1972–73 and new data for 1973–74.

2. Radiowave observations and wind analysis

Soundings were carried out between December 1973 and July 1974. The improved sampling system described in Paper I was used, with a sounding rate of 12 h^{-1}. The pattern of observations again involved a 1 h sequence of soundings near noon, two days per week: usually Wednesdays and Thursdays. In addition, attempts were made each month to obtain three consecutive hours of intensive soundings. The method used for the analysis of the radiowave drifts data was also described in Paper I, and in Manson *et al.* (1973).

3. Irregular and mean winds

Irregular wind amplitudes and mean winds have been obtained for the year 1973–74. The monthly variations of the former are shown in Fig. 1; the plotted line includes the smallest 80% of the values for both components, and is similar to the rms line (Paper I). There are striking similarities between these monthly profiles and those for the previous year (Paper I, Fig. 4). In both cases the winter amplitudes are large, increasing in amplitude to at least ~115 km; while in the equinoxial months of March and April the amplitudes reach a peak at lower heights (~105 km) and fall off sharply above this.

The scale height z_0 of the irregular wind amplitudes, when compared with a constant energy density curve, is defined in

$$\rho_0\langle \Delta u^2+\Delta v^2\rangle \propto \exp(-z/z_0), \qquad (1)$$

where ρ_0 is the ambient density and Δu, Δv are the irregular wind amplitudes. Values of z_0 for 1973–74 over two height ranges (85–100 km, 100–115 km) are shown in Table 1. These are compared with values for the previous year (1972–73), some of which were quoted in Paper I. [Similar magnitudes were obtained by Justus and Woodrum (1973), who used a yearly aggregate of rocket and meteor-radar data.] In general, the z_0 values in the upper height interval are less accurate than below, due to the group height error (Paper I, Section 5). Actual values would tend to be larger in summer, and winter, and even smaller in the spring. Also, there is no clear difference in z_0 values for the zonal (east–west) or meridional (north–south) profiles.

In Paper I, a similarity was noted between the seasonal variations of the heights of reversal for the

Table 1. Scale height (z_0) of gravity wave amplitudes (85–100 km).

Year	Winter circulation (December–February) 85–100 km	Winter circulation 100–115 km	Spring transition (March–April) 85–100 km	Spring transition 100–115 km	Summer circulation (May–July) 85–100 km	Summer circulation 100–115 km
1972–73	8	>8	~20	~3 (April)	6	>6
1973–74	8	~8	24	3	6	~11

mean zonal winds, and the heights of the maxima for the monthly profiles of irregular winds. General mechanisms whereby gravity waves may interact with the mean winds were discussed in some detail.

The data for 1973–74 reveal a similar variation, as seen in the mean zonal winds of Fig. 2 and the profiles of Fig. 1. To make the comparison easier, the appropriate data have been combined in Fig. 3: the heights of reversals for the zonal and meridional winds are shown for 1973–74, as well as for the period 1969–73 (Paper II). There is remarkable yearly consistency in this parameter. The variability of the meridional flow is evidenced by the frequent occurrence of two height reversals, and arrows (e.g., March zonal winds) indicate a significant change within the month. Heights of the maxima from the irregular wind profiles (Fig. 1: an assemblage of east-west and north-south components) and heights from the zonal and meridional profiles are also plotted. On occasions, several maxima occurred in a profile; those with amplitudes within a standard deviation of the principal maximum have also been included. Finally, the graph has been formed by joining the heights of the principal maxima for each month. There is a striking similarity between heights of wind reversals and I.G. wave amplitudes, especially in the zonal component.

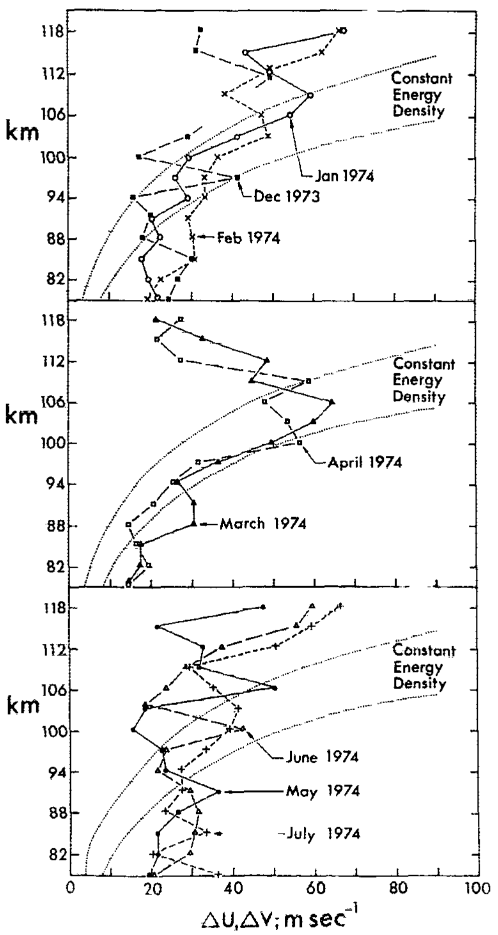

Fig. 1. Irregular wind (gravity wave amplitude) profiles. The amplitudes are closely similar to rms values.

The data for 1972–73 are shown in an identical form (Fig. 4), and high visual correlation is again evident; there are insufficient data, however, for a formal correlation analysis. While it is possible that no causal link exists between these variables, the theory of gravity wave-background flow interactions predict coupling effects of this type (e.g., Jones and Houghton, 1972). A possible explanation is that below the reversal height I.G. waves with phase velocity V_p parallel (rather than anti-parallel) to the background flow U will tend to experience critical levels, i.e., where $V_p = U$. The remaining flux of I.G. waves will begin to experience critical levels above the reversal, until near 105–115 km where for $U \approx 20$–40 m s^{-1} much of the wave flux will have been absorbed or dissipated. Above this level waves of higher phase speed, and possibly even waves generated by the interaction processes, will exist. More quantitative explanations would require numerical modeling involving the inclusion of a wide spectrum of I.G. waves, and the use of zonal and meridional wind cross sections similar to those shown here and in Paper I (Fig. 7).

4. Consecutive intensive sequences of soundings

A number of 2–3 h soundings were scheduled during which profiles were taken at a rate of 12 per hour in an attempt to estimate the amplitude of I.G. waves of longer period ($\tau \gtrsim 60$ min), and the magnitude of hourly changes in the mean flow due to the dissipation (and momentum deposition) of the shorter period waves [cf. the numerical modeling of Jones and Houghton (1972)]. The median zonal and meridional winds for 5 days in 1973–74 are shown in Figs. 5–7. The hourly changes in the wind are comparatively small (10–20 m s^{-1}) at most heights, but in limited

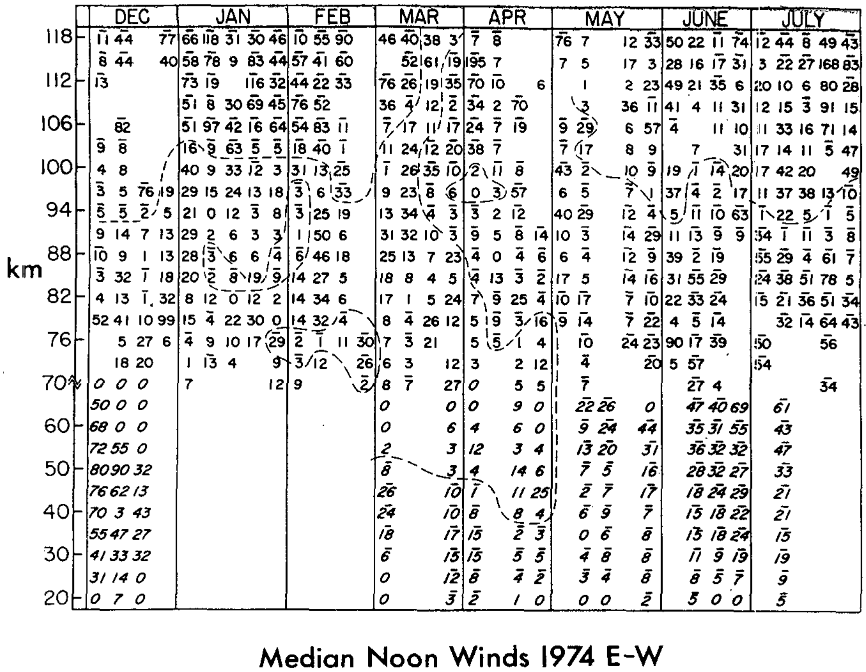

FIG. 2. Time cross section of mean zonal winds at noon. Overbars indicate a negative (westward) wind, and dashed lines mark the heights of reversals between eastward (+) and westward (−) winds. Figures in italics refer to radiosonde data.

height intervals (e.g., 97–103 km on 3 January, 10 April and 3 July) much larger changes occurred.

There are at least three physical processes which could lead to variations in the hourly mean flow: tidal winds, I.G. waves with $\tau \gtrsim 60$ min, and accelerations due to I.G. wave interactions. These will be considered in turn. On the basis of extensive discussions upon the theme of *tidal winds* in Papers I and II, values of ~ 5 m s^{-1} h^{-1} are expected near local noon. Turning to *I.G. waves* with $\tau \gtrsim 60$ min, it has not yet

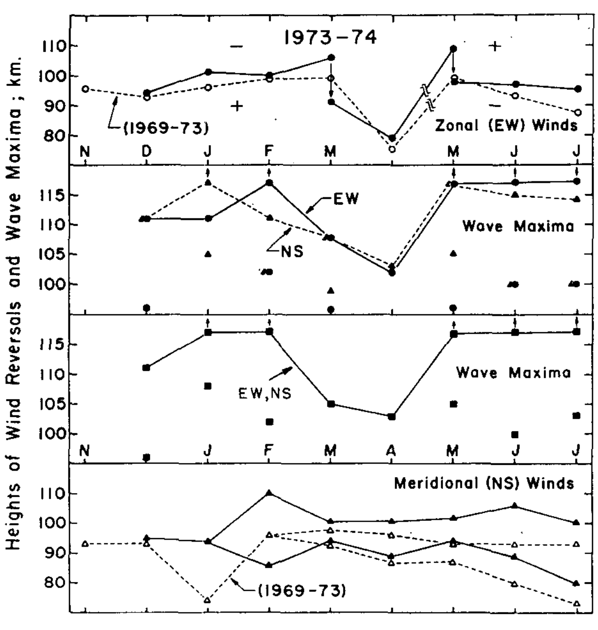

FIG. 3. Heights of mean wind reversals and of maxima from irregular wind (wave amplitude) profiles for 1973–74.

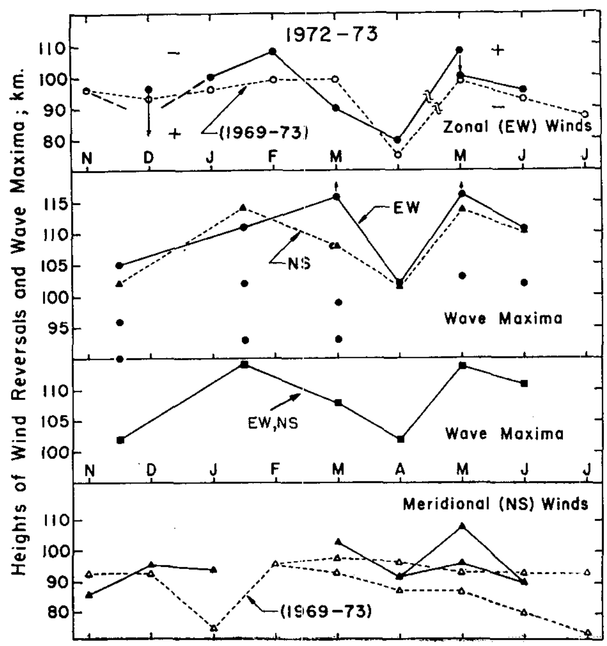

FIG. 4. As in Fig. 3 except for 1972–73.

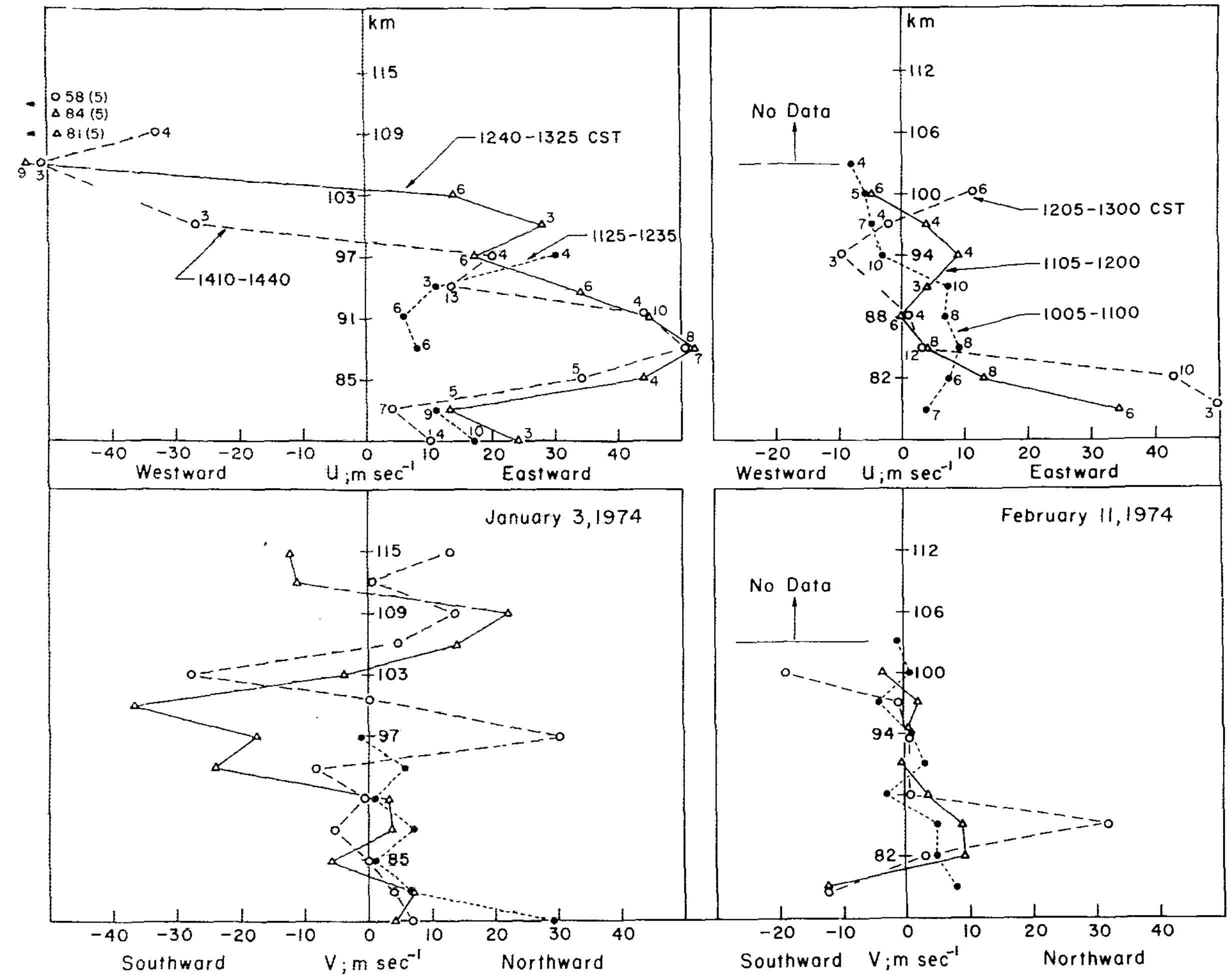

FIG. 5. Median east-west and north south winds for sequences of 1 h atmospheric soundings for 3 January and 11 February, 1974. The number of values available for each median calculation are also shown.

proven possible to apply spectral analysis techniques to ~3 h of winds data ($\lesssim$36 profiles). This is mainly because of gaps in the data: at any one altitude ~60% of the soundings provide useful wind values (Paper I). An estimate was made, however, by comparing $\frac{1}{2}$ h median winds with the 1 h medians of Figs. 5–7. Interestingly, on all days except 10 April, the envelopes of the $\frac{1}{2}$ h profiles retained the same features, while increasing the scatter of values by ~10 m s^{-1} at most heights. Since most of this variation can be explained by waves with $\tau \lesssim 60$ min, it is suggested that on these occasions at least the amplitudes of I.G. waves with $\tau \gtrsim 120$ min were $\lesssim$10 m s^{-1}. However, on 10 April, amplitudes of ~40 m s^{-1} at 100 km are estimated.

There is some evidence, of an indirect nature, that *momentum deposition* by I.G. waves may have occurred on several of these days. Thus on 3 January (Fig. 5), 10 April (Fig. 6) and 3 July (Fig. 7), the largest hourly changes occurred at heights near 100 km where reversals of the zonal and meridional flow occurred (cf. Figs. 2 and 3), and where critical levels might be expected. Even on 11 February (Fig. 5) the largest hourly changes occurred at heights (~80 km) where meridional reversals (Fig. 3) and a small westward cell (~75 km, Fig. 2) existed. Unfortunately, we have not been able to establish that the irregular wind amplitudes underwent any major change at these heights. The data available in any hour, while comprehensive by many other experimental standards, are inadequate in temporal or spatial resolution and continuity for such an analysis. Previously, an association between wave amplitudes and wind reversals was demonstrated (Section 4), but monthly assemblages containing 8–12 h of data were used.

Attempts were made to study the sequences of individual profiles within each of the soundings, to see whether the polarization and spectrum of I.G. waves were such as to provide consistent directions of momentum deposition and acceleration. However

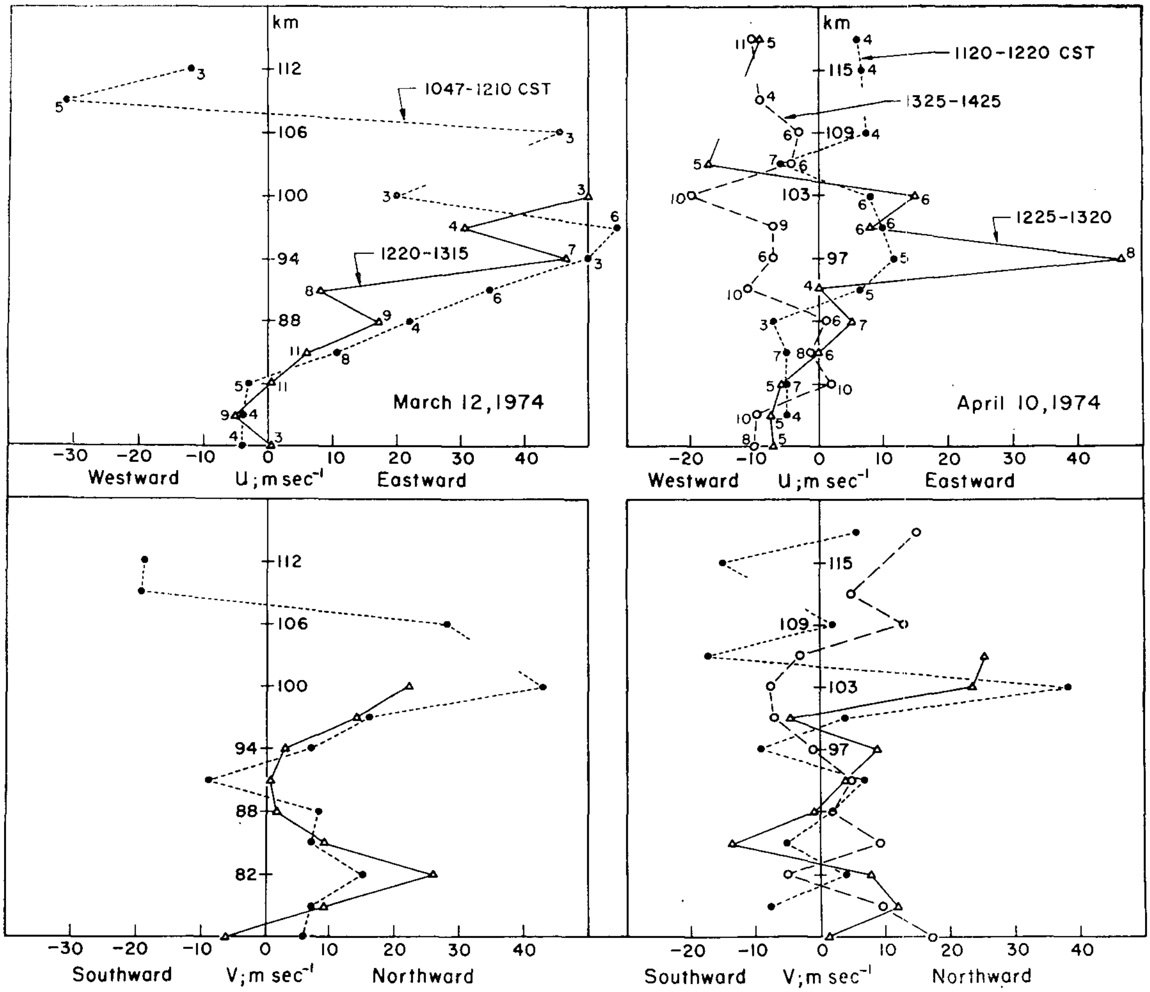

FIG. 6. As in Fig. 5 except for 12 March and 10 April 1974.

although on occasions dominant modes are present (cf. Figs. 1 and 2, Paper I), there are always other modes present which make such an identification by inspection very difficult. Undoubtedly, errors in the individual wind determinations as well as intrinsic variability in the medium are responsible for this. An alternate approach has been to calculate the covariances for the individual irregular wind profiles (i.e., the mean of the east-west and north-south irregular wind products); the mean covariance for the hour and the number of profiles having a particular covariance sign are given in Table 2. It is probably significant that on 3 January, 10 April and 3 July the covariances and their sign consistencies were large, and that the signs were consistent for ~2 h, increasing the possibility of *cumulative* momentum transfer between I.G. waves and the mean flow: these are also the dates on which large hourly changes in mean flow occurred near 100 km. The high covariance for 2 h on 10 April is also consistent with the earlier finding that an I.G. wave of long period ($\tau \gtrsim 120$ min) was present on that day. In conclusion, the hourly changes in the mean wind are consistent with the effects of tidal winds, I.G. waves ($\tau \gtrsim 120$ min), and momentum deposition by I.G. waves, but it has proven difficult to distinguish between these. It is not unlikely that physical coupling between these three "processes" will make such a distinction impossible.

TABLE 2. Coherence of irregular winds.

Date	Covariance* ($m^2 s^{-2}$)			Percent of profiles with consistent covariance sign		
	Hour 1	Hour 2	Hour 3	Hour 1	Hour 2	Hour 3
3 January	+110	+195	+380	43(+)	70(+)	86(+)
11 February	+40	+250	−195	67(+)	50(+)	75(−)
12 March	+200	−15		75(+)	50(−)	
10 April	+560	+655	+30	80(+)	75(+)	54(+)
3 July	−640	−570	+135	83(−)	83(−)	58(+)

* Weighted mean of individual profile covariances.

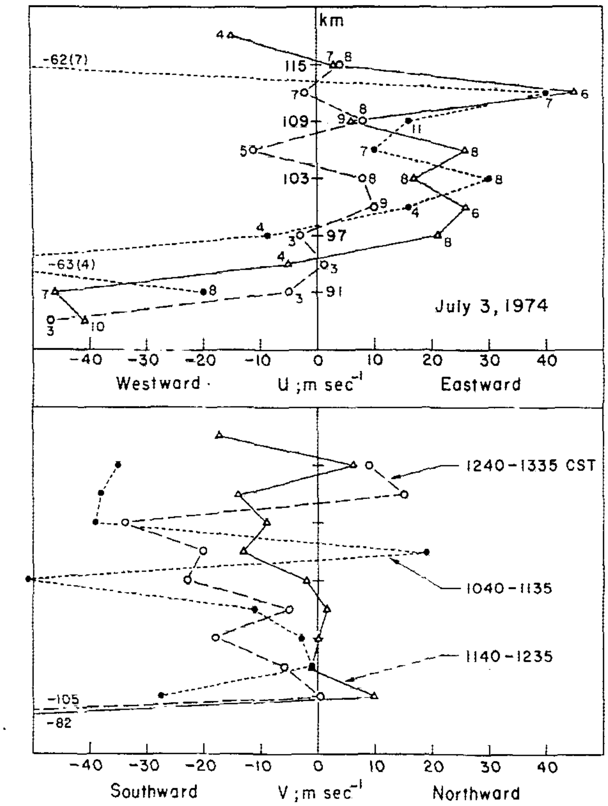

FIG. 7. As in Fig. 5 except for 3 July 1974.

5. Energy and momentum deposition by I.G. waves

By a generalization of the arguments of Hines (1972), we infer the acceleration of the background flow in a layer of thickness H (the scale height), by a plane wave in a region of dissipation to be given by

$$\dot{U}=(\rho_1 u_1^2-\rho_2 u_2^2)\tau_g/(2\tau H\rho_1), \tag{2}$$

where ρ is the density, u the amplitude of the sinusoidally varying wind, τ the wave period, and τ_g the (isothermal) Brunt-Väisälä period: the subscripts 1 and 2 refer to the lower and upper bounds of the layer (when u_2 is zero, the equation simplifies to that given by Hines).

Calculations of $\dot{U}$ for the profiles of Fig. 1 were made using $\tau\approx 60$ min, $\tau_g\approx 5$ min, $H\approx 6.5$ km, and for values of ρ from the U. S. Standard Atmosphere. Values for profiles similar to those for winter, spring and summer months are 8, 0 and 9 m s^{-1} h^{-1} respectively from 94–100 km, and 12, 70 and 8 m s^{-1} h^{-1} respectively from 105–112 km. It must be stressed that such values of acceleration will probably not add cumulatively throughout the seasons, since I.G. wave propagation will occur for a distribution of azimuthal angles which is as yet unknown. However the values are appropriate to coherent wave systems of the type discussed above in Section 4. Hence, as noted by Hines (1972), "unless the cancellation is severe, the inferred acceleration . . . must be recognized as a major contributor to the dynamical balance of the region."

If dissipation of the I.G. wave energy does not lead to systematic acceleration of the mean flow, it will lead to direct heating, and the creation of turbulence through such processes as convection or shear instability (Hodges, 1967), i.e., down the scale spectrum. An estimate of the eddy diffusion coefficient K can result from a development by Hines (1970, 1973). When $\lambda_x \gg \lambda_z$ (horizontal and vertical wavelengths) it may be shown that

$$K=0.014\,\lambda_z^4(\tau_g H\lambda_x)^{-1}. \tag{3}$$

Taking $\lambda_z\approx 12$–20 km (Paper I), $\lambda_x\approx 10\,\lambda_z$ (Justus, private communication), and the other values as above, the value of K is from 1–5×10^3 m^2 s^{-1} near 100 km. Unfortunately, it is not possible to calculate K as a function of height, as λ_x and λ_z are not adequately known as a function of height. This value is however comparable to values of K ($\sim 10^3$ m^2 s^{-1}) obtained by Justus (private communication) using rocket data.

6. Conclusion

Intensive soundings of the atmosphere (12 profiles per hour) during 1972–73 and 1973–74 have provided profiles of the mean flow and of irregular winds (I.G. wave amplitudes). The seasonal variations of these data were remarkably similar in the two years, and are consistent with energy and momentum exchange between waves and the "background flow."

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