Diurnal Variations of the Summertime Wind and Force Field at Three Midwestern Locations[1]

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ABSTRACT

A comprehensive summary of diurnal wind variations in the midwestern region of the United States is presented. Analyses are based on seven summers of four per day soundings at Fort Worth, Tex., Topeka, Kan., and International Falls, Minn. It is found that the diurnal oscillations are most prominent at Fort Worth, of significant amplitude at Topeka, and, although of lesser amplitude, still detectable at International Falls. An analysis is made of the forcing required to account for that part of the wind oscillation which cannot be attributed to Coriolis effects. This analysis indicates that the forcing is comparatively small at Fort Worth where the wind oscillations are largest owing to a resonance there with natural inertial oscillations. Significant forcing is present at higher latitude stations even though the manifestation of the forcing in the wind field is somewhat smaller in amplitude. The data suggest that forcing mechanisms at low and high altitudes may propagate to cause wind oscillations in the middle levels.

1. Introduction

This study concerns the behavior of a complex but systematic summertime diurnal oscillation in the wind field over the central United States. Diurnal variations in the physical characteristics of the atmosphere have long been studied. Chapman and Lindzen (1970) discuss the daily variations in barometric pressure that occur on a global basis. Such variations in pressure naturally lead to daily variations in the movement of air. In addition to various local-scale or mesoscale diurnal fluctuations, such as land-sea breeze systems, mountain-valley flows, etc., daily variations in the winds on the large scale have been reported by many investigators.

Johnson (1955), in a harmonic analysis of the wind at 100–150 mb over England, found a clear dominance of the diurnal and semidiurnal harmonics over all others with the magnitude of the variations of the order of 0.3 m s^{-1}. Similar analyses were performed for a number of levels between the surface and 10 mb at Washington, D. C. (Harris, 1959) and Terceira, Azores (Harris *et al.* 1962). A companion study by Finger *et al.* (1965), which included eight more mid-latitude stations, showed amplitudes again of the order of 0.3 m s^{-1} for the diurnal and semidiurnal oscillations with a slight decrease in amplitude from south to north. Some stations, particularly those with continental climates, exhibited distinct maxima in the vertical distribution of the amplitude near 1 km height. At such stations, the diurnal oscillation was greater at most tropospheric levels than the diurnal component over stations not exhibiting such a low level maximum. Hering and Borden (1962) analyzed rawin data during July 1958 for stations in the continental United States reporting 6 h observations. They found that the diurnal oscillation of the wind over the central United States is much more complex than that seen in other areas. Three levels of maximum amplitude of the departure wind, at roughly 1, 5 and 12 km, separated by levels of little variation were found in this region with maximum amplitudes ranging from 1 to 3 m s^{-1}. The departure wind vectors rotate clockwise with time with considerable phase variation with height.

Diurnal wind oscillations in the boundary layer were studied by Bonner (1968) who found a pronounced maximum in the frequency of occurrence of large

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boundary layer oscillations on the Kansas–Oklahoma border in this country. This core of low-level, high-speed winds which exhibits a rather large amplitude diurnal oscillation with a nocturnal maximum has been called the low-level jet and has been shown by Bonner to be largely a summertime phenomena of the central United States. Bonner's study also showed the low-level jet oscillation to be accompanied by rather large diurnal variations in the middle and upper troposphere.

Wallace and Hartranft (1969) analyzed 15 years of twice-daily wind observations in the Northern Hemisphere, most at 00 and 12 GMT with some at 03 and 15 GMT. The diurnal variations over the central United States were found to have a complex magnitude and phase structure up to 100 mb, suggestive of influences other than or in addition to that of the diurnal tide. For example, the diurnal variation at 500 mb in this area has greater amplitude and is directed at right angles to that farther north. At 200 mb, the oscillation over this area is again significantly large in amplitude and 180° out of phase with the oscillation at 500 mb. These authors were able to show that a large part of the variant wind behavior over the central United States occurs during the summer months.

Wallace and Patton (1970) considered the diurnal temperature fluctuations which would result from adiabatic vertical motions implied by the divergent characteristics of the diurnal wind oscillation. They found significant vertical fluctuations in the diurnal temperature variations over stations in the continental United States and over tropical stations with vertical wavelengths of 5–10 km and temperature differences of the order of 1°C above the tropopause and somewhat less than this between the boundary layer and the tropopause.

Wallace and Tadd (1974), using data similar to those of Wallace and Hartranft (1969) but with a more accurate computational procedure, showed that the diurnal variation of wind is significantly influenced by surface topography to at least 28 km height.

Willson (1975) has given a discussion of similar diurnal oscillation phenomena over Australia using 12 years of upper air observations. He finds oscillations in the lowest few kilometers which are influenced by land-sea boundaries, sloping terrain and frictional effects in various combinations depending on location. At higher altitudes, a layer of roughly constant phase exists throughout much of the troposphere with vertically propagating modes above about 16 km.

The purpose of this paper is to examine in greater detail the behavior of the diurnal wind oscillation system that occurs in the central United States during the summer. In particular, it is desired to study the persistence and regularity of the system, the differences in the mean flow conditions attending the oscillations at different latitudes, the degree of relationship between the oscillation at various heights and at various latitudes, and the "forcing" which is necessary to account for the observed diurnal oscillation.

2. Data

The data for this study consisted of observed values of wind speed and direction for each of four times (00, 06, 12, 18 CST) on each day of three summer months (July, August, September) for the seven consecutive years 1958 through 1964. Observations at each time were available at 24 separate levels, ranging from the surface to 18 km above sea level, for three stations: Fort Worth, Tex. (33°N, 97.5°W, 180 m), Topeka, Kan. (39°N, 96°W, 267 m), International Falls, Minn. (49°N, 93.5°W, 360 m). Gaps in the data were eliminated by inserting average values for the appropriate month, time and level so as to provide a continuous record. More than 90% of the data are real and not interpolated.

Departure vectors were computed by vectorially subtracting the mean wind for each day from the wind at each observation time. Departure vectors so determined were resolved into zonal and meridional components and they, along with the components of the daily mean wind, provide the basis for the analysis described herein.

3. Analysis of average values of overall wind and departure wind

In Fig. 1, the seven-summer averages of the components of the departure wind at Fort Worth, Topeka and International Falls are shown. Fort Worth exhibits a strong oscillation in the lowest kilometer of the atmosphere with amplitude of roughly 2.5 m s^{-1}. The strength of this oscillation decreases rapidly with height to a level of 2.5 km, where the amplitude of the departure wind is less than 0.5 m s^{-1}. The maximum southerly wind component occurs near 0000 (local time), with the maximum westerly component near 0600.

Above the 2.5 km level, the amplitude of the diurnal oscillation increases once more with altitude to a height of about 5 km. At this level there is a definite maximum in the amplitude of the departure wind, with a value of about 1.5 m s^{-1}. The phase is such that the strongest southerly wind occurs near 1200 and the strongest westerly wind at about 1800.

The amplitude of the departure wind then decreases again to a minimum of somewhat less than 1 m s^{-1} near the 8–9 km level and then increases with altitude to a maximum of about 1.5 m s^{-1} near 12 km. At 12 km, the maximum in the southerly wind component occurs at about 1800 and the maximum in the westerly component occurs near 0000. Above this altitude the amplitude of the departure wind decreases and from about 15 km to the upper limit of data at 18 km remains fairly uniform at roughly 0.5 m s^{-1}. All vertical phase shifts mentioned here and in the remainder of this paper do not include the slight additional lag factor due to the

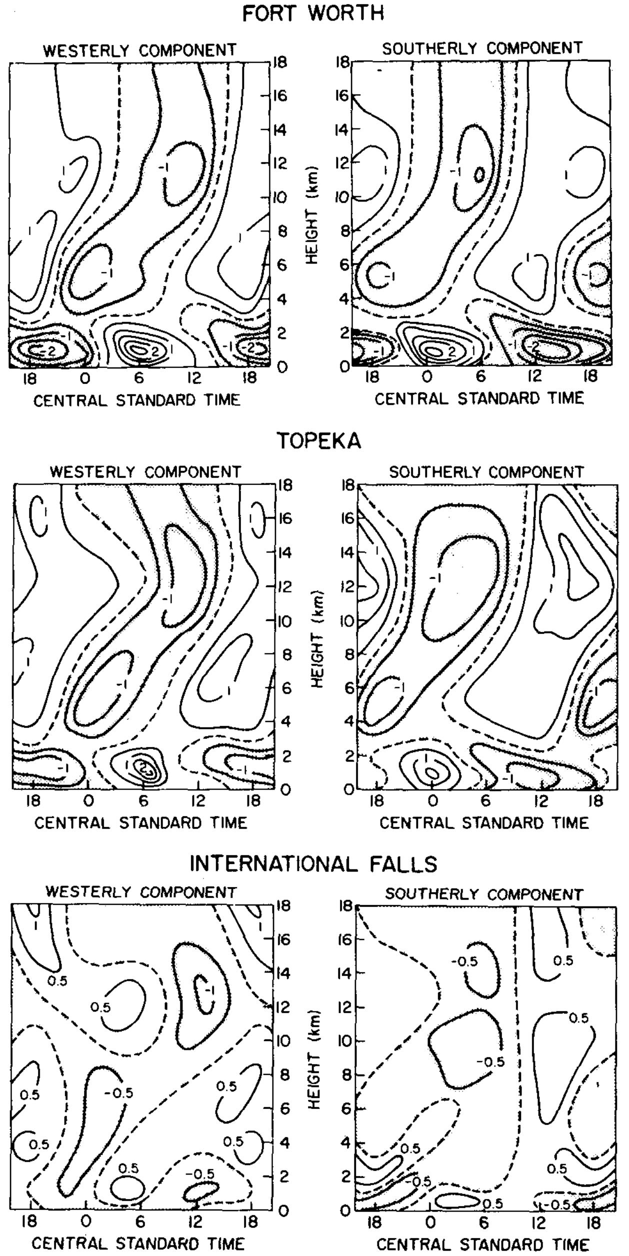


FIG. 1. Seven-summer average distribution of the components (m s^{-1}) of the departure wind vector at Fort Worth, Tex., Topeka, Kan., and International Falls, Minn.

ascension time of the radiosonde balloon—about 1 h from the surface to 18 km.

The seven-summer average of the departure wind at Topeka is similar in a number of ways to that at Fort Worth. The oscillation cell in the boundary layer extends to about 2 km and has an amplitude of about 2 m s^{-1}. Two cells appear in the troposphere, one centered at about 5 km and a higher one near 12 km. Both have amplitudes of roughly 1.4 m s^{-1}. The upper cell appears to be somewhat greater in vertical extent and is more clearly delineated, particularly in the southerly component. The maximum southerly wind occurs at 0000 CST at 1 km, between 0600 and 1200 at 5 km, and just before 1800 at 12 km. The maximum westerly wind follows after 6 h at each level.

The general form of the diurnal oscillation at Fort Worth is very similar to that at Topeka with amplitudes and phases being nearly equal. The situation at International Falls is quite different. The amplitudes of the wind oscillations are much smaller. The oscillation in the boundary layer is not nearly so regular as at lower latitudes and a middle level oscillation seems to occur mainly in the zonal component.

Single-summer averages of the time-height variation of the departure wind at Fort Worth and Topeka showed oscillation cells very much like the seven-summer averages in Fig. 1. The season-to-season consistency that was exhibited at Fort Worth and Topeka was not at all apparent at International Falls. For example, the summer average for 1958 at International Falls showed a layer of significant southerly departure winds centered at 10 km at 1800 while the summer average for 1964 exhibited a layer of significant northerly departure at the same altitude and time. One feature of the wind system at International Falls which is conspicuous by its very reduced amplitude is the boundary layer oscillation. None of the seven summers exhibited a boundary layer oscillation of amplitude approaching 1 m s^{-1} at International Falls, although five of seven summers exhibited an oscillation in the meridional component of nearly 2 m s^{-1} amplitude at middle levels. The center of this oscillation was most often near 10 km, but varied from 6 to 14 km in altitude, and consistently exhibited a southerly maximum between 1200 and 1800.

Comparison of monthly averages of the departure wind system of the three stations showed Fort Worth to maintain the most consistent pattern. At Topeka, the boundary layer oscillation is present most months but is often quite weak. Cellular structure in the monthly time-height patterns at Topeka is frequent but the cells vary considerably in amplitude and height. Oscillation cells at higher altitudes (~12 km) are both stronger and better organized in the southerly component. Monthly averages of the time-height patterns of departure wind at International Falls showed little month-to-month consistency. Oscillation cells appear but occur at different altitudes and with differing amplitudes from month to month. The most consistent feature seems to be nearly constant phase with height above 3 or 4 km, with maximum southerly departure at about 1500 and maximum westerly departure between 1800 and 2400.

Fig. 2 shows hodographic representations of the mean wind at all levels and departure winds at each observation time at 1, 5 and 12 km for the seven-summer period at each station. The mean wind hodograph shows points

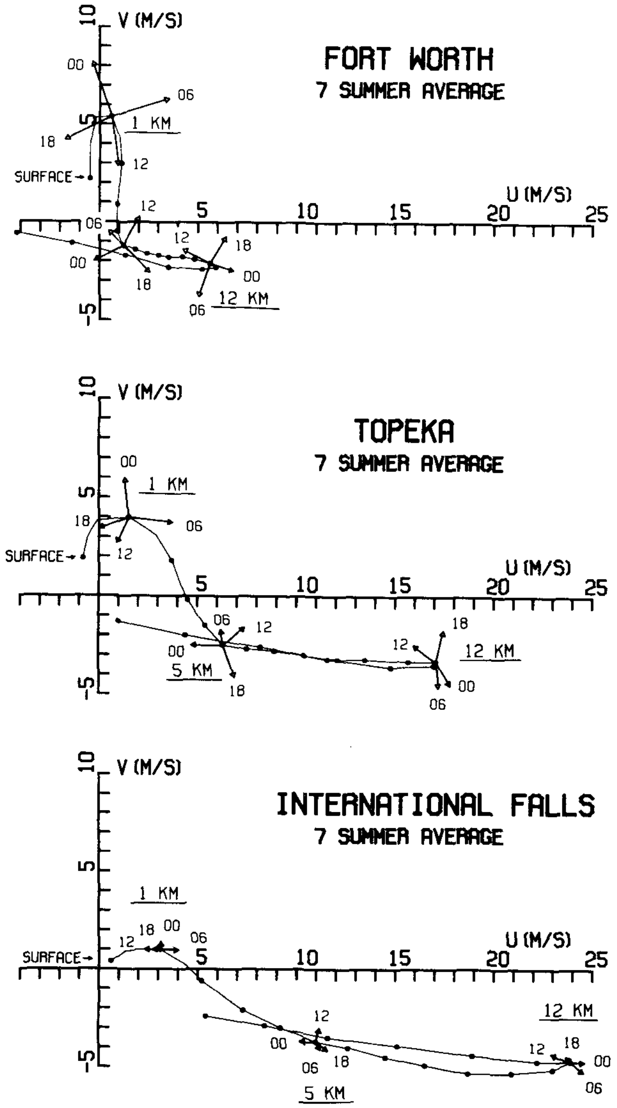


FIG. 2. Hodographs of seven-summer average, daily mean wind at Forth Worth, Topeka and International Falls along with average departure vectors at each observation time at 1, 5 and 12 km. Points on the hodograph are for the surface and at increments of 1 km height above sea level. Observation times are 00, 06, 12 and 18 CST.

at the surface and at intervals of 1 km above sea level. The mean wind exhibits maxima at some high level around 12 or 13 km at each station with maximum values increasing with latitude. Additionally, Fort Worth and Topeka each show local maxima at about 1 km with local minima between 2 and 5 km. Both stations show strong veering between the surface and 5 km and above the level of maximum wind. The variation at International Falls is more in magnitude than direction although the mean hodograph is qualitatively similar to those at the lower latitudes. The latitudinal change here shows the transition from what is basically a subtropical climate in summer (Fort Worth) with strong flow off the Gulf of Mexico at low levels to an area (International Falls) which in summer remains deeply under the influence of the mid-latitude westerly flow with only a hint of the southerly flow component at low levels.

The departure winds in Fig. 2 at Fort Worth exhibit nearly uniform clockwise rotation at 1, 5 and 12 km and vary little in magnitude through the day. At Topeka, the behavior of the departure vectors is similar to that at Fort Worth but is somewhat less regular in rotation and magnitude. At the same levels at International Falls, the departure vectors are quite irregular, partially as a consequence of their considerably smaller magnitude.

Fig. 3 shows a seven-summer mean meridional cross section of the southerly departure component at each observation time. Strong nocturnal boundary layer convergence is seen to exist with divergence during the daytime. Maxima in the meridional components of divergence and convergence at the 5 and 12 km levels are shifted about 6 h from the boundary layer cycle.

4. Non-inertial forcing of the departure wind

Since diurnal and inertial frequencies are of the same order of magnitude, it is of interest to assess the distribution of non-inertial forcing necessary to account for the observed tropospheric wind oscillations. The term "non-inertial forcing" is used here to represent an influence necessary to account for that part of the diurnal oscillation in the wind which cannot be attributed to the inertial Coriolis force. If the departure wind vector at a given altitude is decomposed into its Fourier representation, the diurnal harmonics of its components may be represented as

$$\tilde{u}(t)=A\sin(\nu t)+B\cos(\nu t),$$
$$\tilde{v}(t)=C\sin(\nu t)+D\cos(\nu t),$$

where $\nu=(2\pi/24\text{ h})$ and A, B, C, D are determined from the Fourier decomposition of the departure wind data. One may define functions F and G from the relations

$$F=(\partial\tilde{u}/\partial t)-f\tilde{v},$$
$$G=(\partial\tilde{v}/\partial t)+f\tilde{u}.$$

From equations of motion partitioned so as to isolate the local and inertial accelerations of the departure wind components as above, F and G can be interpreted as forcing functions which include all real forcing or acceleration effects other than the direct Coriolis acceleration. Inserting the Fourier representation of the wind data, the diurnally varying components of the non-inertial forcing necessary to account for the diurnal harmonics of the observed wind oscillations can be calculated.

This procedure was carried out using the seven-summer averaged values of the departure vector at each observing station and at each level. To illustrate, Fig. 4a shows a vector representation of the oscillation

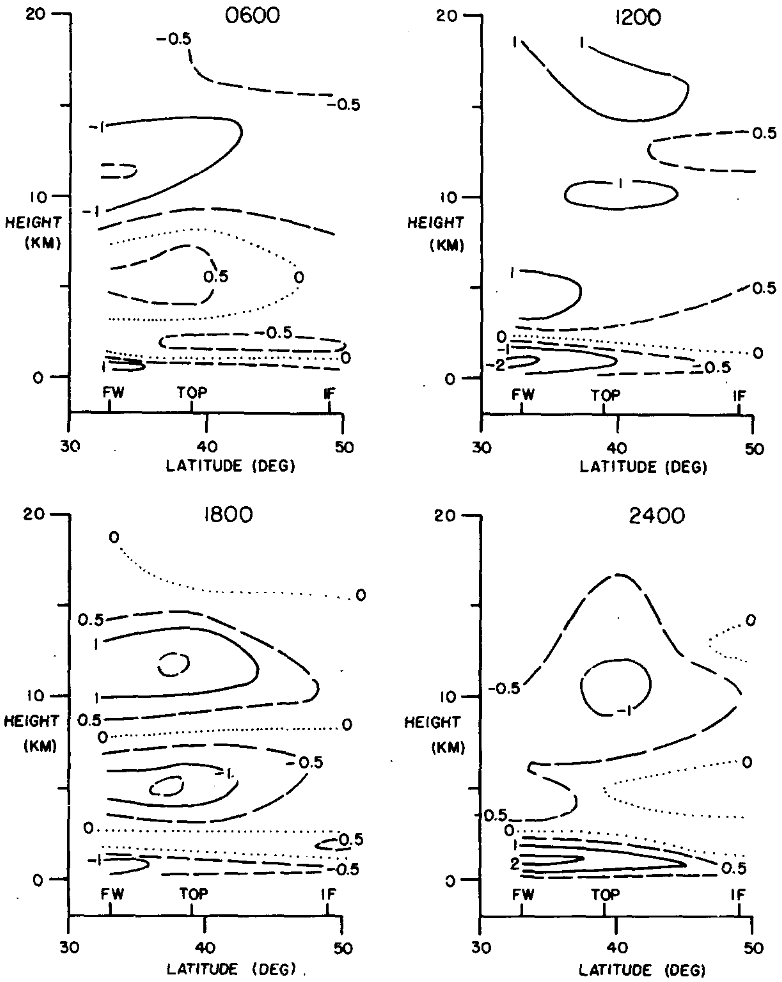
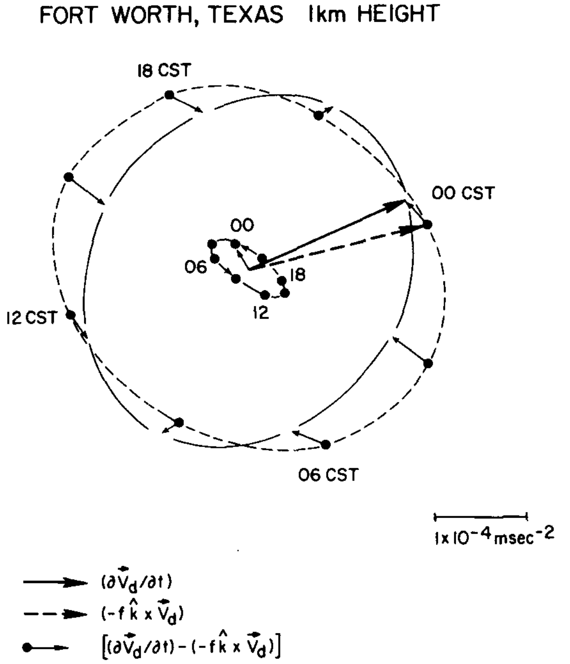


FIG. 3. Seven-summer average meridional cross sections of the southerly component ($m\ s^{-1}$) of departure vector at each observation time.

at Fort Worth at the 1 km level. The solid broad vector is the local acceleration, $\partial \tilde{V}_d/\partial t$, where $\tilde{V}_d$ is the vector whose components are the diurnal harmonics of zonal and meridional departure wind components. The broken vector is the Coriolis acceleration of this vector harmonic, $-f\mathbf{k}\times \tilde{V}_d$. Both these vectors are seen to rotate in a clockwise sense with time. The solid thin vector is the vector difference between the local and inertial acceleration and represents the non-inertial force. As seen in Fig. 4a, this vector happens to rotate *counterclockwise* at this location and elevation and its end point describes an ellipse with major axis aligned from northwest to southeast. Fig. 4b shows the non-inertial force vector juxtaposed with the diurnal harmonic of the departure vector at various times of the day for the 1 km height at Fort Worth. The opposite rotation of the departure vector and the non-inertial force vector bring them into all possible directional juxtapositions in a 24 h period.

Fig. 5 shows vector diagrams of the non-inertial force at 1, 5 and 12 km for each of the three stations. Force vectors are drawn for 0000 CST and the dots represent the position of the endpoints of the force vectors at 3 h intervals. At Fort Worth, the force vector rotates counterclockwise with time at all three altitudes with about a 180° phase shift between 1 and 5 km and about 90° phase shift between 5 and 12 km. In comparison to the other two stations, the amplitude of the non-inertial force at Fort Worth is considerably smaller even though the wind oscillation is largest there. That is to say, the larger amplitude wind oscillation at Fort Worth is more a reflection of near inertial-diurnal resonance than of large non-inertial forcing. The endpoint of the force vector at each level at Fort Worth describes an ellipse, over 24 h, whose major axis is oriented generally NW–SE. At International Falls, the forces are larger, also rotate counterclockwise at each level, but describe ellipses whose major axes are oriented N–S at 1 km, NW–SE at 5 km and NE–SW at 12 km. The phase shift between 1 and 5 km is only about 90° and the shift from 5 to 12 km is nearly −90° leaving the 1 and 12 km forces nearly in phase. Note that even though the oscil-



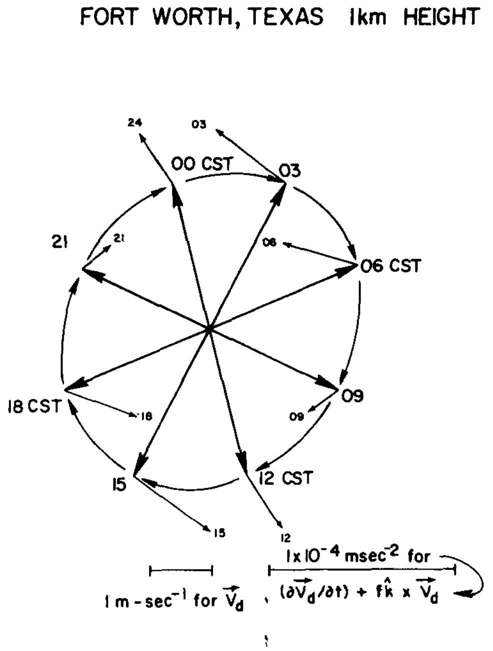


Fig. 4a. Vector representation of the local acceleration (broad, solid vector) and the Coriolis acceleration (broad, broken vector) of the diurnal harmonic of the wind departure vector. The solid, thin vector is the difference between the two broad acceleration vectors and represents the non-inertial force (see text). The vector endpoints are represented at 3 h intervals.
Fig. 4b. Non-inertial force vector, as defined in Fig. 4a, juxtaposed with the diurnal harmonic of the wind departure vector. Vectors are again represented at 3 h intervals.

lation of the departure vector at International Falls is not nearly so regular as at the other two stations, the corresponding non-inertial force oscillates in a very well behaved manner. At Topeka, the non-inertial force at 1 km oscillates in a counterclockwise sense along a nearly degenerated ellipse oriented NNW–SSE, while at 12 km the ellipse is fuller with an axis orientation ENE–WSW. Note that at 5 km at Topeka, the non-inertial force vector oscillates in the opposite sense, that is, clockwise along nearly the same axis as at 1 km.

To get a better appreciation for the complex phase relations of the non-inertial forces operating in these mid-western locations, the components are represented in Figs. 6–8 on time-height cross sections along with the diurnal harmonics of the departure wind components. Values of the force components shown are in units of 10^{-5} m s^{-2} and the wind components in units of m s^{-1}. The reader should take note of the expanded vertical scale below the height of 3 km. It should be emphasized at this point that, as explained in Section 2, the departure vectors were computed each day by subtracting the daily mean wind from each of the four observed winds. Thus, the time series of departures, from which the diurnal harmonic is extracted, is relative to a time series of daily mean wind which contains much of the longer period variation. For this reason, $\tilde{u}(t)$ and $\tilde{v}(t)$ in Figs. 6–8 are good representations of $u'(t)$ and $v'(t)$ in Fig. 1. The most notable features of such a comparison are the large amplitudes at Fort Worth and Topeka, the apparent existence of a semidiurnal influence at International Falls in Fig. 1, and the apparent lack therefore at Fort Worth and Topeka. Even at International Falls, however, the amplitude of the diurnal harmonic (Fig. 8) is comparable to the peak values of departure shown in Fig. 1 suggesting that most of the variation shown in Fig. 1 is of diurnal and not semi-diurnal period.

The magnitude of non-inertial forcing is clearly larger at International Falls and Topeka than at Fort Worth where the amplitude of the wind oscillation is largest. There is a strong phase shift with height in the boundary layer—nearly a phase discontinuity—at all three stations. Above 1 km at Topeka and International Falls, the meridional component of forcing $(\partial\tilde{v}/\partial t+f\tilde{u})$ exhibits similar behavior with values in-phase at some low and upper levels (roughly 1 and 12 km) with about a 9 h lag at some intermediate level (about 8 km at Topeka and 4–6 km at International Falls). At Fort Worth, the phase shift in this component between 1 and 9 km is similar to that at higher latitude stations but there is not the strong phase advance at the higher altitudes at Fort Worth that are exhibited at Topeka and International Falls.

The zonal components $(\partial\tilde{u}/\partial t-f\tilde{v})$ at all three stations show values nearly in-phase at a low and a high altitude (at 2 km and at 13, 12 and 10 km respectively at Fort Worth, Topeka and International Falls). There tends to be a slight phase advance at an intermediate level at Fort Worth and Topeka but this is not in

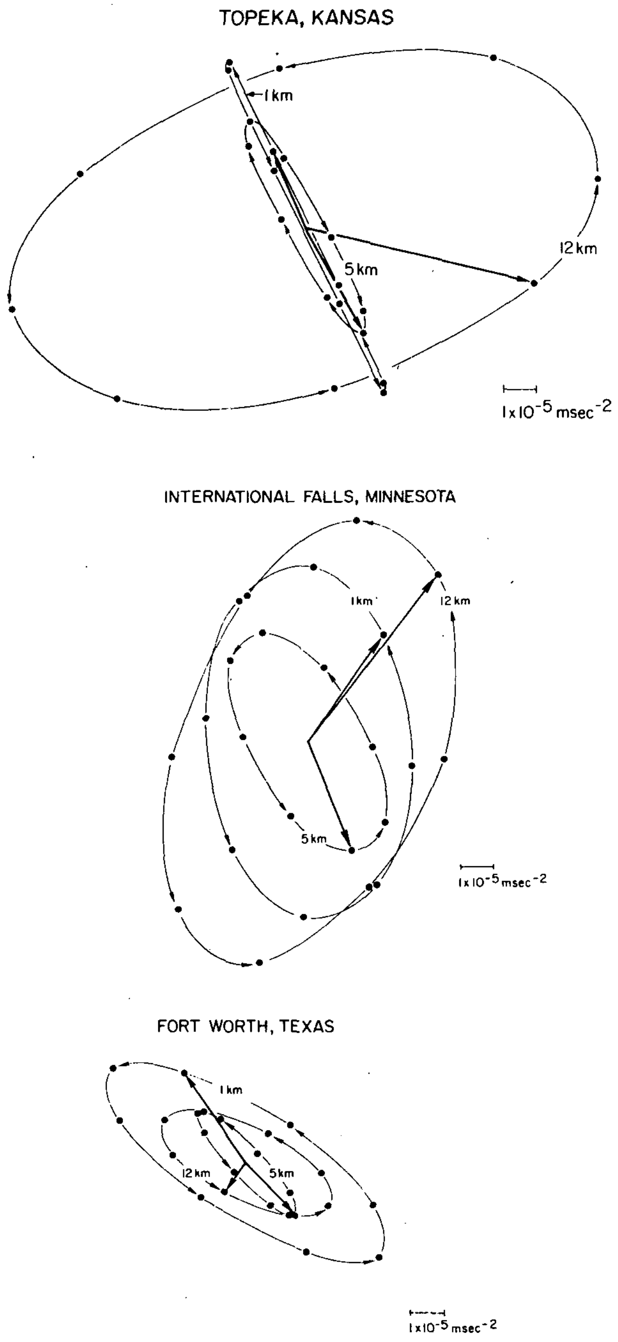


FIG. 5. Non-inertial force vector, as defined in Fig. 4a, at 1, 5 and 12 km and at 3 h intervals for Fort Worth, Topeka and International Falls. Vectors are shown for 0000 CST at each level.

evidence at International Falls. Also, Topeka exhibits a moderate local maximum near 6 km whereas this feature is not present at the lower and higher latitudes.

These graphs indicate that the amplitude of the diurnal wind oscillation in the central United States is controlled to a great extent by the degree of inertial-diurnal resonance but that there is significant diurnal forcing going on in the mid and upper troposphere. The forcing appears to be strongest at high and/or low altitudes and there is a suggestion that these influences may propagate to middle levels to cause diurnal wind oscillations at those levels. Such a propagating influence is more clearly indicated in the meridional component of the force than in the zonal component.

As a very preliminary test of this hypothesis, a cross-spectral analysis was performed on the time series of departure wind magnitudes at 1, 5 and 12 km at each station for the summer of 1958. The coherence (see Panofsky and Brier, 1963), a parameter somewhat analogous to the square of a correlation coefficient between a pair of time series, was computed to assess the degree of relationship between the oscillations at various levels. Table 1 shows the coherence values found for the diurnal frequency between selected series. At Fort Worth, the coherences between 1 and 5 km and between 12 and 5 km at the diurnal frequency are relatively high while the coherence between 1 and 12 km is quite small. A similar relationship holds true at Topeka but the highest coherence at International Falls is between 1 and 12 km. This distribution of values suggests that the middle cell may be coupled to independent oscillations at lower and higher levels at Fort Worth and Topeka. At International Falls, the middle oscillation cell is much weaker and nearly non-existent so is not coherent with lower or higher cells. Coherences between stations are also shown in Table 1. Coherences at 1 km are much larger than at the higher levels and are generally greatest between Fort Worth and Topeka.

5. Conclusions

This study has shown that the structure of the diurnal variation of the wind field in the summer over the

TABLE 1. Estimates of coherences between time series of magnitudes of departure wind for Fort Worth, Tex. (FTW), Topeka, Kan. (TOP) and International Falls, Minn. (INL). Summer 1958.

Series 1		Series 2		
Station	Height (km)	Station	Height (km)	Coherence estimates
FTW	1	FTW	5	0.175
FTW	1	FTW	12	0.062
FTW	5	FTW	12	0.402
TOP	1	TOP	5	0.345
TOP	1	TOP	12	0.005
TOP	5	TOP	12	0.488
INL	1	INL	5	0.021
INL	1	INL	12	0.228
INL	5	INL	12	0.068
FTW	1	TOP	1	0.714
FTW	1	INL	1	0.533
TOP	1	INL	1	0.558
FTW	5	TOP	5	0.117
FTW	5	INL	5	0.065
TOP	5	INL	5	0.066
FTW	12	TOP	12	0.277
FTW	12	INL	12	0.034
TOP	12	INL	12	0.012

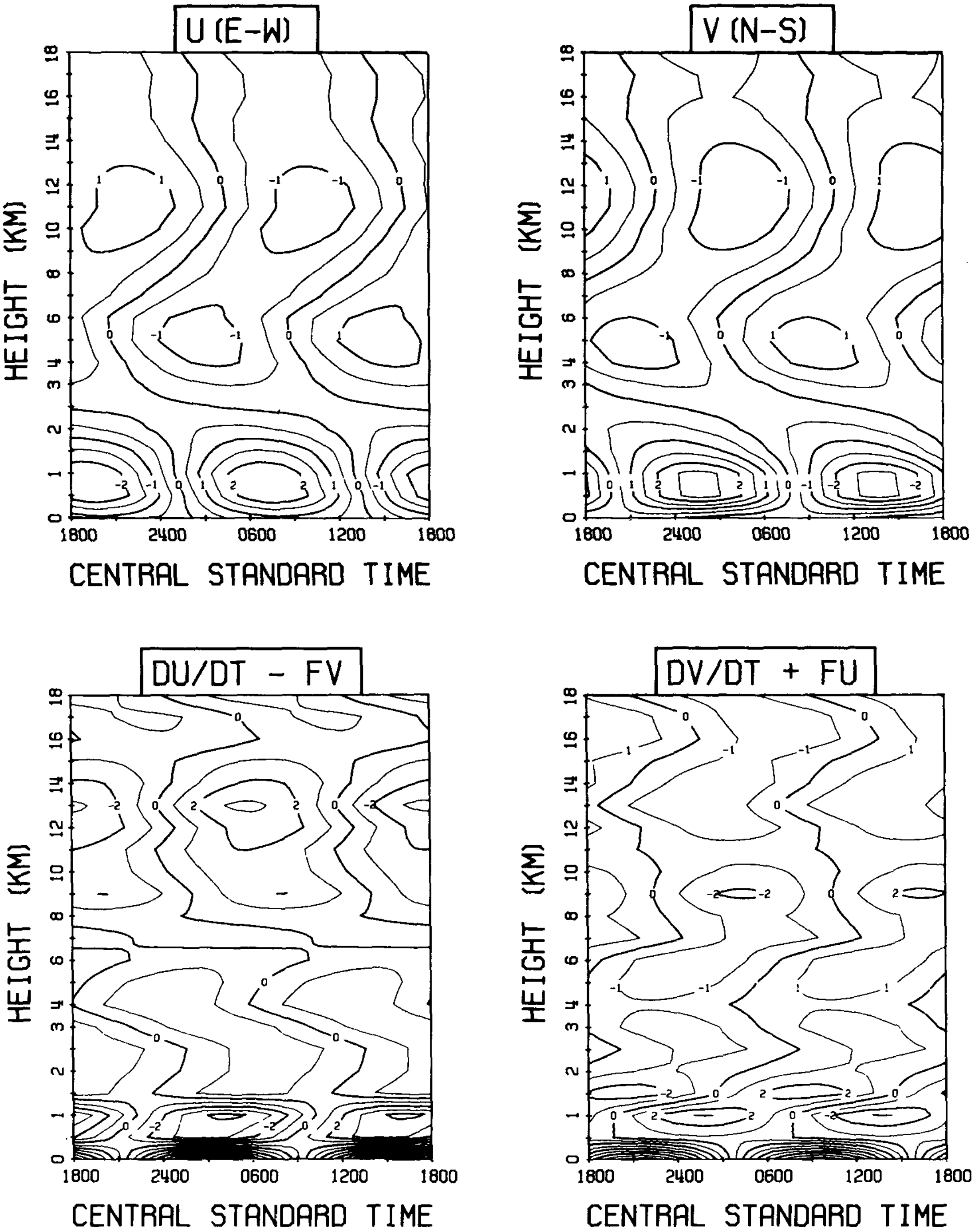


FIG. 6. Zonal and meridional components (m s^{-1}) of the diurnal harmonic of wind departure vector and the non-inertial force (10^{-5} m s^{-2}) as defined in Fig. 4a for Fort Worth.

central United States, as previously observed by Hering and Borden (1962), Bonner (1968) and Wallace and Hartranft (1969), is indeed a regular and persistent feature of the atmosphere. The seven-summer average of the diurnal oscillation system at Fort Worth shows the same basic features as the one-month analysis of Hering and Borden; namely, strong centers of diurnal wind oscillation at 1, 5 and 12 km with amplitudes of 1–3 m s^{-1} and a significant phase variation with height. Further, stations at higher latitudes (Topeka and International Falls) show similarly prominent oscillations at higher levels but with somewhat smaller amplitudes and different vertical variations. Besides being successively further away from the latitude of resonance between diurnal and inertial oscillations, these stations also exhibit distinctly different mean wind conditions,

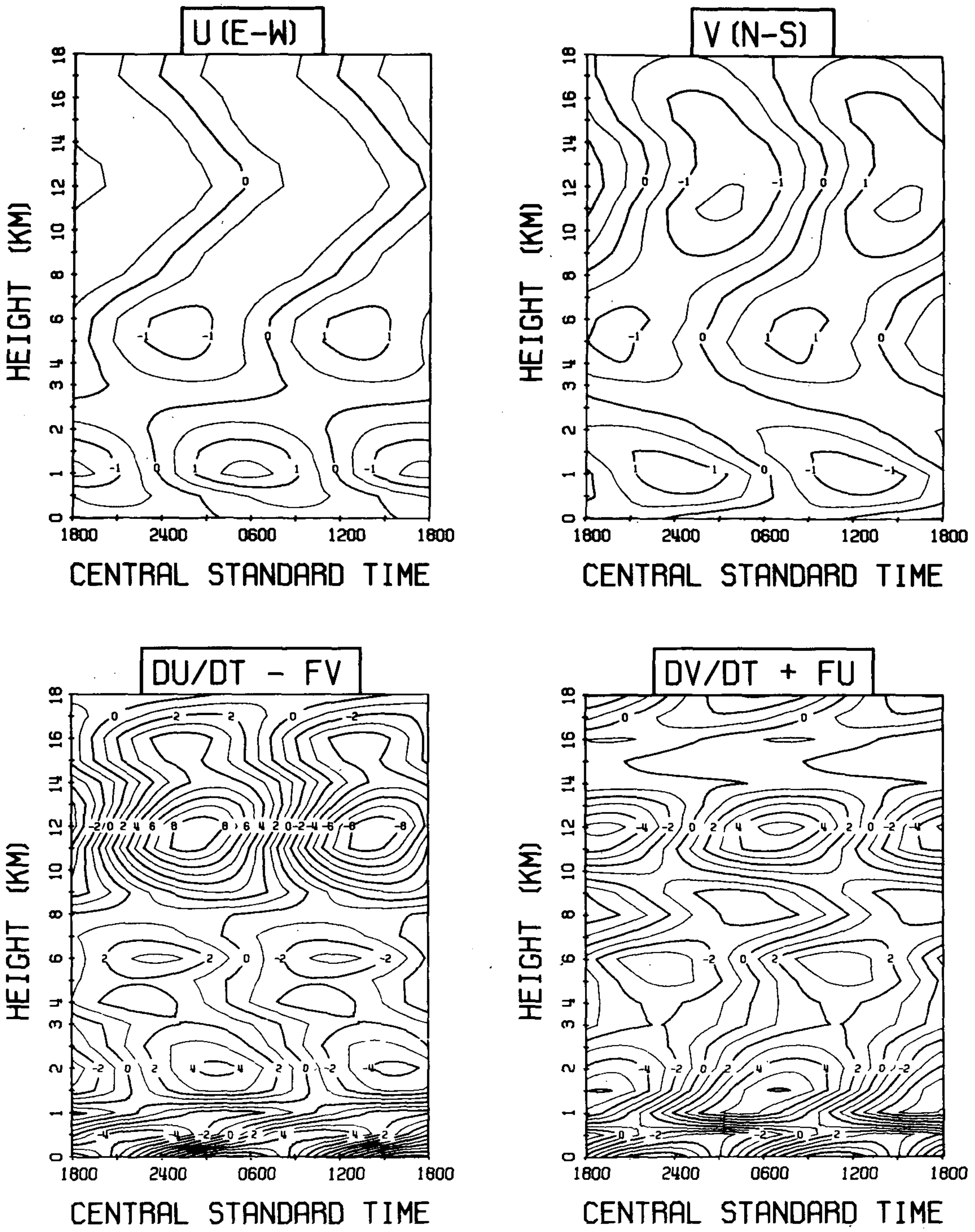


FIG. 7. As in Fig. 6 except for Topeka.

both of which must certainly contribute to the differences in the diurnal wind oscillations at the three stations. All three stations exhibit a relative maximum in the wind speed profile near 12 km at all times of the day. The strength of this maximum increases going north between the three stations. Fort Worth shows a secondary local maximum at all times of the day near the 1 km level (low-level jet) while such is exhibited at Topeka only during the nighttime hours. International Falls does not show a low-level jet structure but does exhibit a weak diurnal wind oscillation at low levels. The direction of the prevailing winds in the boundary layer is southerly to southwesterly at Fort Worth and Topeka whereas it is more southwesterly to westerly at International Falls. Between the surface and the 5 km level, the mean wind veers through 147° at

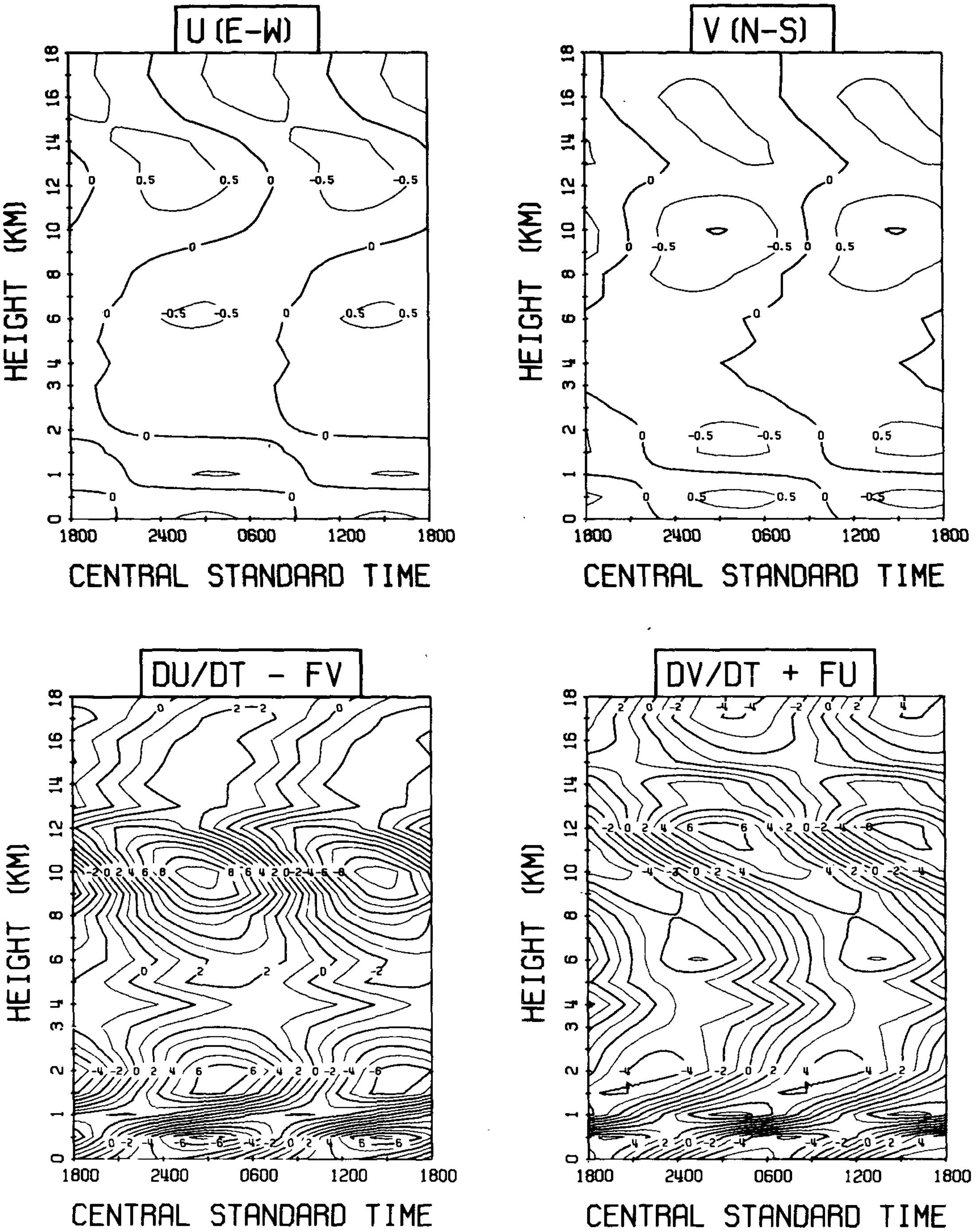


Fig. 8. As in Fig. 6 except for International Falls.

Fort Worth, through 133° at Topeka, but only through 64° at International Falls.

An analysis of the forcing, other than the Coriolis forcing, which is required to account for the diurnal harmonic of the wind oscillations was carried out. In general, this force was found to oscillate diurnally in such a way that its orientation varied in a counterclockwise sense over 24 h, i.e., a rotation generally opposite to that of the departure vector rotation. The magnitude of this forcing was found to be smallest at Fort Worth, where the amplitude of the wind oscillation was generally largest, and increased going northward through Topeka to International Falls. The vertical change of phase of this forcing suggests that the source of forcing may be at high and low levels with some propagation of the influence to middle levels of the troposphere. Such a coupling between the middle level wind oscillation, noted especially at Fort Worth and Topeka, with higher and lower oscillations was supported by a very preliminary statistical analysis of the coherence between time series of wind departure magnitudes at 1, 5 and 12 km. However, further study and statistical testing must be performed before such coupling can be considered well established and defined.

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