Diurnal Wind Variation in the Troposphere and Lower Stratosphere over Japan

By Atsushi Yoshida* and Isamu Hirota

Geophysical Institute, Kyoto University

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Abstract

The diurnal variation of wind at nine levels between 1000 and 100 mb over eight Japanese stations is obtained from the balloon data during the period of 1956 and 1958. The result of computation indicates that the structure and behavior of the diurnal tidal motion in the troposphere and lower stratosphere are strongly affected by surface topography.

This fact is also confirmed by a comparison study of vertical distributions of the diurnal meridional wind oscillation at a coastal, an inland and a mid-ocean stations in middle latitudes. The dominance of vertically propagating modes in the lower atmosphere over the coastal station, and somewhat large magnitude of trapped modes originated in the planetary boundary layer over the inland station are found.

Difference between the observation and theory is also discussed.

1. Introduction

Daily variations of the wind, pressure and temperature in the upper atmosphere have been investigated by many authors for many stations, to present the detailed pictures of the vertical structure of diurnal and semidiurnal tidal motions below 30 km (Johnson, 1955; Harris, 1959; Harris *et al.*, 1962, 1966; Carlson and Hastenrath, 1970).

In their study of the summer daily wind oscillation over the central United States, Hering and Borden (1962) found that the instantaneous wind vectors at the peak amplitude levels (1, 5 and 12 km) appear to be associated with surface topography. Wallace and Hartranft (1969) and Wallace and Tadd (1974) extensively investigated the topographic influence using 12-hourly wind difference vectors. Wallace and Tadd reported that the topography influences the diurnal wind oscillation up to at least 28 km.

However, a detailed quantitative study of the planetary-scale structure of the upper-air tidal motion has not been made yet, for lack of adequate number of determinations of the diurnal wind oscillation.

On the other hand, the theory of the diurnal tide excited by the heating due to the stratospheric and mesospheric ozone and the tropospheric water vapor was obtained by Lindzen (1966) and Kato (1966). Lindzen's theory is generally in good agreement with observations between 30 and 60 km for latitudes from 8°S to 64°N (Reed *et al.*, 1969). However, the theory is inadequate to explain the structure and behavior of the observed diurnal tidal motion in the lowest 30 km of the atmosphere. Observed features of the seasonal variation of the diurnal tide, such as almost a complete reversal of phase between summer and winter at 30 mb level (Wallace and Tadd), cannot be explained by the theory, either. Wallace and Tadd suggested the effects of the mean wind field, the forcing due to land-sea distribution and irregularities in terrain height, as the possible causes of discrepancy between the observation and the theory.

Therefore, further quantitative studies of the diurnal tide in the lower atmosphere for more stations distributed over the globe are desired in order to be compared with the results of theoretical studies. In this regard, the purpose of the present study is to report the observed diurnal wind variation over Japan and the overall picture of its vertical and seasonal dependence.

* Present affiliation: School of Meteorology, University of Oklahoma, U.S.A.

A comparison with results for a few other locations is also made to find some discrepancy between the observation and the theory.

2. Data and computational procedures

The data used in the present study mainly consist of the monthly-mean values of the observed wind speed and direction for each of six times daily (0300 and 1500 GMT in 1956*/0000, 0600, 1200 and 1800 GMT in 1958). Nine levels from 1000 to 100 mb are chosen for this analysis at eight stations located between 33°N and 46°N (see Table 1).

Table 1. List of stations used

	Latitude, N	Longitude, E	Elevation, m
Shionomisaki	33°27'	135°46'	69.0
Yonago	35 26	133 21	7.9
Tateno	36 03	140 08	27.2
Wajima	37 23	136 54	6.9
Sendai	38 16	140 54	39.8
Akita	39 43	140 06	9.9
Sapporo	43 03	141 20	18.1
Wakkanai	45 25	141 41	3.2

These data are taken from the data books, *Geophysical Review* and *Aerological Data of Japan*, both of which have been published monthly by Japan Meteorological Agency.

The method of computation used here is based on that reviewed by Chapman and Lindzen (1970, p. 63). Assuming that the wind in the upper air consists of a prevailing, a diurnal and a semidiurnal wind components only, *i.e.*,

$$\begin{bmatrix} U \\ V \end{bmatrix} = \begin{bmatrix} u_0 + \Delta u_0 \\ v_0 + \Delta v_0 \end{bmatrix} + \begin{bmatrix} u_1 \cos(15t - \sigma_{u_1}) \\ v_1 \cos(15t - \sigma_{v_1}) \end{bmatrix} + \begin{bmatrix} u_2 \cos(30t - \sigma_{u_2}) \\ v_2 \cos(30t - \sigma_{v_2}) \end{bmatrix}, \quad (1)$$

a harmonic analysis is carried out for each of U (southward wind component) and V (eastward wind component) sequences for each month. Here, u_0 and v_0 are prevailing winds of the U and V components respectively and t is a local time. Secular variations Δu_0 and Δv_0 are taken into account. Following Carlson and Hastenrath (1970), we used in Eq. (1) cosine functions instead of sine functions. In this case, the resulting phase σ_{u_1} (σ_{v_1}) indicates an hour angle at which a maximum diurnal wind of u_1 (v_1) occurs, so that $\sigma/15^\circ$ corresponds to its local time in

* The 6-hourly Rawin observation was not routinely made at most Japanese stations prior to July 1957.

hour.

The semidiurnal component, however, cannot be derived by a least-square method from our time series of observations for lack of time resolution. Hence we will hereafter denote the diurnal oscillations of the southward and eastward wind components, *i.e.*, the first harmonics in Eq. (1), as u and v respectively for convenience.

Annual mean (and seasonal mean) amplitude and phase of the diurnal component are calculated from the monthly values of the first harmonics in Eq. (1). We adopt the following definition of seasons;

Symbols	Name	Months included
J	summer	May to August
E	equinox	March, April, September, October
D	winter	November to February
Y	annual mean	all twelve

The radius of the probable-error circle of the annual mean of twelve monthly values [hereafter, for brevity, referred to as the probable error or *P.E.*] is calculated to show the reliability of the results.

Moreover, for the purpose of estimating the reliability of the monthly-mean wind speed and direction listed in the data book, an attempt is also made to obtain differently the monthly mean value with higher accuracy, based on the daily data at Tateno in the same period (1956 and 1958) taken from *Aerological Data of Japan*. The levels of altitude chosen for this calculation are every 2 km between 2 and 20 km.

3. Results

Before presenting the result of computation in detail, we compare the reliability between the two sets of data at Tateno; one is based on the monthly-mean values as original data, and the other the daily values. Shown in Fig. 1 are the amplitudes of u and v together with the probable errors; circles denote the results derived from the latter data, while crosses do those derived from the former. No significant difference is found between the two, since magnitudes of their probable errors are nearly equal. This result assures that the analysis for other stations would have the same reliability as those calculated from the daily values.

The results of the harmonic analysis for the annual mean values at individual stations are illustrated in Fig. 2, and are tabulated in Ap-

Fig. 1 Amplitudes of the diurnal variation of southward wind component u and eastward wind component v for the annual mean in 1956 and 1958 over Tateno, together with the probable error bars. Circles are determined based on the daily data of wind direction and speed; crosses are based on the monthly mean data.

pendix. The results for other seasons (J, E, D) are not reproduced here.

As a representative of those of the eight stations, let us examine the Tateno's vertical distribution of amplitude and phase in detail. For the u component, the amplitude has three maxima at 3, 8 and 12 km with magnitude of the orders of 0.5, 0.6 and 1.0 m/sec respectively. The phase angle above the planetary boundary layer increases with altitude up to about 10 km, and remains constant (about 15° or 0100 LT) or decreases slowly at higher altitude. Results for other stations also show the similar features of distribution (see Fig. 2(a)), though the maximum of amplitude at 3 km (700 mb) at Tateno is found at lower level (about 2–0 km or 850–1000 mb) and the second maximum at 8 km is at 5 or 9 km (900 or 300 mb) for most stations. From these results it seems to suggest that the maximum amplitude at 5 km found by Hering and Borden (1962) over the central United States depends on local topography.

For v , the maxima of amplitude are observed at 4, 10 and 16 km over Tateno, with magnitude of about 0.5, 0.6 and 1.4 m/sec respectively. These levels differ in altitude with a range of about ± 2 km depending on locations (Fig. 2(b)). The phase progresses upward up to the highest altitude of the present analysis (100 mb) at most stations, though it behaves somewhat differently from station to station.

Topographic influence on the diurnal tidal

motion is seen more clearly in Fig. 3, where the harmonic dial vectors are plotted on the maps of 1000, 500, 200 and 100 mb levels for u (Fig. 3(a)) and v (Fig. 3(b)) respectively. The values at Osan, Korea are taken from the paper of Harris *et al.* (1966).

Eight Japanese stations may be classified into two groups, depending on which side of the east and the west of the Japanese Islands the station is located in. Shionomisaki, Tateno and Sendai are of the first group, the east coast stations; on the other hand, Yonago, Wajima, Akita, Sapporo and Wakkanai are of the second group, the west coast stations.

The diurnal variation at 1000 mb mainly consists of a land-sea breeze, since the harmonic dial vectors of the two groups point to almost the opposite directions each other. As for u , the effect of differential heating due to the land-sea distribution seems to become weak at 500 mb, since there is no large systematic difference in phase distributions between the two groups at this level. Some other small influence, however, still remains at higher levels as noted by Wallace and Tadd (1974).

Compared with u , the v component appears to be influenced much more by local condition, and it is difficult to find a systematic feature of v at higher levels. This irregularity may be partly due to the influence of the spatial inhomogeneties in the mean flow, in the heating force, and/or in topography.

Fig. 2 Amplitudes and phases of the diurnal variations of southward wind component u (a) and eastward wind component v (b) for the annual mean in 1956 and 1958 over 8 Japanese stations.

Finally, to see briefly the seasonal variations of u and v , we display the summer (season J) and winter (season D) means of harmonic dial vectors for two levels in Fig. 4. There appears large seasonal phase variation at some stations, *e.g.*, Sendai (100 mb), Wajima and Yonago (500 mb), although no clear relation between the two seasons is found. However, it is noteworthy that an irregular pattern remains at higher altitude in winter than in summer. This may be due to the predominance of the strong mean westerly flow in wintertime.

4. Comparison with other stations' results and the theory

It is of quite interest to compare the present

result with the earlier ones for other middle-latitude stations obtained by other authors. In Fig. 5, we display the annual mean amplitudes and phases for Osan, Korea ($37^{\circ}6'N$, $127^{\circ}2'E$), Fort Worth, Texas ($32^{\circ}50'N$, $97^{\circ}3'W$, 173 m), and Terceira, Azores ($38^{\circ}45'N$, $27^{\circ}5'W$, 53 m), all obtained by Harris *et al.* (1966), together with those for Tateno. Note that Osan is located at coast as well as Tateno, Fort Worth is at inland in the Great Plains, and Terceira is at mid-ocean of the North Atlantic; the last two stations are considered to be free from the effect of the land-sea distribution. A comparison only for the meridional wind component u is made here, since its probable error is smaller than that for the zonal component v (Fig. 1).

Fig. 3 Harmonic dial vectors of the diurnal variations of southward wind component u (a) and eastward wind component v (b) for the annual mean in 1956 and 1958 for the 100-, 200-, 500- and 1000-mb levels. Directions of vectors measured clockwise from the downward direction denote the phase angles (or the local hours of maximum), 0–360 degrees (or 0000–2400 LT). Lengths of them show the amplitudes on the scale shown by the inset in the top map. Vectors are centered on the stations. Values at Osan, Korea are taken from Harris *et al.* (1966).

The amplitude and phase of the diurnal tide in an isothermal atmosphere ($T=260^\circ\text{K}$) for equinoctial condition is also illustrated in the figure, which is reproduced following Lindzen (1966, 1967). We assume here that the equinoctial condition can be regarded as the representative of the annual mean condition with good reliability.

At Osan, the phase progresses rapidly with altitude from the surface up to 3 km, and its value is nearly constant between 3 and 7 km. It changes abruptly about 150 degrees (10 hours)

between 8 and 10 km, and is again constant (about 30° or 0200 LT) above this level. Osan's phase distribution resembles those at Tateno (Fig. 5), Shionomisaki, Sendai and Akita (Fig. 2(a)), except for the levels between 5 and 8 km. Contrary to these observations, the result from Lindzen's theory shows a downward progression of phase in the atmosphere below 20 km. We can say, therefore, that the upward propagating modes originated in the planetary boundary layer are relatively strong in the troposphere over the coastal station in middle latitude, while in the

Fig. 4 Same as Fig. 3 but for the summer (J) and the winter (D) in 1956 and 198 for the 100- and 500-mb levels.

lower stratosphere they will have amplitudes comparable to the downward propagating modes excited in the stratosphere.

The amplitude distribution for Osan below 20 km shows a similar character to that of Tateno in that it oscillates with height in the troposphere, though the magnitude of the former is several times smaller.

At Fort Worth, the phase fluctuates with altitude with the largest deviation of about four hours (60 degrees) from 0000 LT. More notable features, which are not found at any other stations, in the vertical distribution of u are the appearance of the maximum amplitude (0.89 m/

sec) at 5 km and the gradual decrease in amplitude with altitude with small fluctuation. These are suggestive of rather great magnitudes of the trapped modes at inland-type stations.

On the other hand, Terceira shows a vertical distribution of amplitude different from those at other stations. The amplitude increases slowly upward and its magnitude is slightly less above the tropopause than that predicted by the theory. Above this level the phase regresses upward very gradually; however it regresses downward below this level contrary to the downward phase progression predicted by the theory. Since the mid-ocean station is considered not to be much in-

Fig. 5 Amplitudes and phases of the diurnal variations of southward wind component u for the annual mean in 1956 and 1958 at Tateno; Osan, Korea; Terceira, Azores; Fort Worth, Texas. The values for stations except Tateno are taken from Harris *et al.* (1966). Dashed lines are those for the latitude of 37.5°N for an isothermal atmosphere ($T=260^\circ\text{K}$) of the equinoctial condition, which is calculated based on Lindzen's (1966, 1967) theory.

fluenced by local condition such as topography, we believe that the most portion of the deviation at Terceira from the theoretical prediction is probably due to the causes independent of the station type.

From the discussion above we can conclude that, at middle latitudes, the upward propagating modes originated in the planetary boundary layer are dominant at the coastal station, while somewhat great magnitudes of the trapped modes probably excited by the surface temperature variation or by the terrain height can be observed at the inland station. Delay in phase from the theory in the stratospheric level over all stations will be modified partly by considering the basic flow in the stratosphere. Some of the discrepancy between the observation and the theory in the troposphere are also probably due to the effects of the mean wind, the horizontal temperature gradient and the convection in this layer.

5. Conclusions

The observational study presented here has shown an overall picture of the vertical structure of the diurnal wind variation at several Japanese stations. The result shows that the altitude of the maximum amplitude found by Hering and Borden (1962) varies depending on local topographic conditions.

The maps of harmonic dial vectors in the Far East region exhibit the spatial variation of the diurnal tidal motion at each level. They confirm more quantitatively the conclusions of Wallace

and Hartranft (1969) and Wallace and Tadd (1974) for the local topographic influence on the tidal field up to the high level. It is also indicated that the local irregularity of the tidal motion in middle latitudes is notable at higher altitude in winter than in summer.

The comparison study of the vertical distributions of u at the three different types of locations in middle latitudes clearly shows the influence of land-sea distribution. Furthermore, the comparison between the inland station and the mid-ocean station suggests the influence of the surface on the diurnal tidal motion in the upper atmosphere, such as by the daily variation of the surface temperature or the terrain height, as pointed out by Wallace and Tadd, and others. This is in contrast to Siebert's (1961) conclusion that the atmospheric response to the surface temperature variation is very small.

More extensive and reliable presentation of the harmonic dial vectors for upper-air tidal motions will give us full information concerning the planetary-scale feature of the topographically induced tidal waves and other non-migrating waves with higher wavenumbers.

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Appendix

The annual means of amplitude (AMP), phase (PHA), and probable error (PE) of the observed diurnal wind variations at eight Japanese stations, for the period of 1956 and 1958. Amplitude and probable error: m/sec. phase: degrees.

(a) Southward wind component (u)

Height	Shionomisaki			Yonago			Tateno			Wajima		
	AMP	PHA	PE	AMP	PHA	PE	AMP	PHA	PE	AMP	PHA	PE
1000 mb	0.65	43	0.10	1.66	231	0.14	0.69	69	0.11	0.74	217	0.17
850 mb	0.25	193	0.15	0.70	55	0.16	0.24	242	0.15	0.54	75	0.17
2 km							0.50	236	0.12			
700 mb	0.54	276	0.17	0.17	1	0.18	0.53	255	0.18	0.34	109	0.17
4 km							0.32	272	0.17			
500 mb	0.18	282	0.21	0.11	304	0.22	0.40	291	0.23	0.08	91	0.26
6 km							0.38	294	0.25			
400 mb	0.57	293	0.20	0.15	12	0.24	0.44	333	0.27	0.28	283	0.28
8 km							0.60	350	0.27			
300 mb	0.61	313	0.28	0.37	332	0.26	0.51	346	0.33	0.42	357	0.33
10 km							0.70	2	0.34			
200 mb	0.60	319	0.31	0.27	347	0.41	0.93	23	0.40	0.36	53	0.33
12 km							0.97	13	0.38			
150 mb	0.33	19	0.23	0.39	359	0.32	0.79	23	0.24	0.55	20	0.31
14 km							0.67	13	0.30			
16 km							0.64	10	0.26			
100 mb	0.53	6	0.22	0.19	25	0.34	0.67	10	0.26	0.48	326	0.26
18 km							0.47	8	0.24			
20 km							0.32	23	0.24			

(b) Eastward wind component (v)

Height	Shionomisaki			Yonago			Tateno			Wajima		
	AMP	PHA	PE	AMP	PHA	PE	AMP	PHA	PE	AMP	PHA	PE
1000 mb	0.47	270	0.17	0.43	130	0.15	0.81	109	0.09	0.14	53	0.09
850 mb	0.42	83	0.18	0.46	68	0.15	0.41	103	0.12	0.25	28	0.11
2 km							0.45	128	0.16			
700 mb	0.29	182	0.20	0.18	143	0.11	0.49	146	0.12	0.25	135	0.16
4 km							0.52	161	0.16			
500 mb	0.10	309	0.20	0.09	5	0.23	0.10	176	0.17	0.19	25	0.24
6 km							0.15	62	0.20			
400 mb	0.50	325	0.23	0.49	296	0.30	0.07	324	0.29	0.16	177	0.25
8 km							0.39	87	0.37			
300 mb	0.08	144	0.30	0.79	302	0.30	0.20	136	0.23	0.40	335	0.42
10 km							0.59	138	0.40			
200 mb	0.39	176	0.33	0.76	322	0.33	0.30	226	0.33	0.34	271	0.35
12 km							0.49	207	0.33			
150 mb	0.18	271	0.24	0.15	251	0.34	0.10	244	0.27	0.13	341	0.26
14 km							0.33	197	0.33			
16 km							1.09	2	0.39			
100 mb	0.46	145	0.29	0.53	357	0.26	1.43	2	0.33	0.37	35	0.47
18 km							0.58	41	0.30			
20 km							0.77	60	0.38			

Sendai			Akita			Sapporo			Wakkanai		
AMP	PHA	PE	AMP	PHA	PE	AMP	PHA	PE	AMP	PHA	PE
0.75	72	0.19	0.75	275	0.18	0.66	225	0.14	0.04	62	0.18
0.25	140	0.23	0.42	98	0.16	0.59	67	0.11	0.69	36	0.18
0.45	185	0.35	0.23	257	0.18	0.14	201	0.22	0.24	355	0.18
0.47	250	0.24	0.43	267	0.21	0.35	295	0.23	0.27	265	0.23
0.43	268	0.28	0.57	286	0.20	0.32	305	0.28	0.21	253	0.26
0.40	226	0.49	0.64	326	0.37	0.29	293	0.37	0.06	349	0.39
0.32	38	0.42	0.67	38	0.31	0.31	127	0.48	0.57	115	0.47
0.89	8	0.53	0.38	122	0.27	0.33	175	0.52	0.39	17	0.51
0.11	6	0.42	0.42	1	0.22	0.56	334	0.31	0.22	60	0.32

Sendai			Akita			Sapporo			Wakkanai		
AMP	PHA	PE	AMP	PHA	PE	AMP	PHA	PE	AMP	PHA	PE
0.44	29	0.19	1.54	239	0.14	0.34	248	0.13	0.17	237	0.14
0.22	63	0.25	0.38	25	0.16	0.28	50	0.14	0.14	30	0.14
0.35	176	0.25	0.23	21	0.15	0.16	64	0.17	0.26	140	0.15
0.58	162	0.20	0.14	167	0.20	0.15	39	0.20	0.24	171	0.25
0.23	152	0.19	0.13	170	0.24	0.27	303	0.35	0.05	102	0.30
0.82	188	0.33	0.09	301	0.34	0.59	271	0.36	0.92	234	0.43
0.42	73	0.36	0.54	25	0.40	0.66	338	0.69	0.70	226	0.39
0.69	117	0.88	0.13	179	0.25	0.70	36	0.90	0.61	299	0.47
0.18	85	0.30	0.36	114	0.31	0.46	172	0.39	0.23	93	0.42

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日本上空の対流圏および下部成層圏に於ける風の日周期振動

吉田 淳*・廣田 勇

京都大学理学部地球物理学教室

1956年と1958年の気球観測データを用いて、日本上空 1000 mb—100 mb の間の 9 高度に於ける風の日周期振動（大気潮汐）を求めた。対流圏および下部成層圏では、この日周期の大気潮汐振動は地形に強く影響されることがこの解析でも確かめられた。日本のような中緯度の地点でははっきりとした振動の季節変化は検出できないが、地点による不規則さは冬の方がより上層まで現われている。これは冬の大気の性質（jet 気流など）によるものと考えられる。

更に、中緯度の異なった地形環境にある気球観測地点での解析結果を他の論文から引用し、今回の解析と比較した結果では、海岸・大陸内部・大洋上空での日周期振動に興味深い違いが発見された。Laplace の潮汐方程式の解から予想される propagating modes と呼ばれ、励起源から上下に遠くまで振動が伝わるような波は観測では海岸上空で強く、trapped modes と呼ばれ、励起源からあまり遠くまで振動が伝わらないような波は、大陸内部上空で比較的強いことがわかった。

対流圏・下部成層圏に於ける、観測事実と Lindzen (1966, 1967) の理論的モデルとの食い違いは、地形の影響（主に海陸分布・地表温度の日変化・大山脈など）や平均場などを考慮することによって部分的に補正することができるであろう。

* 現在所属：米国オクラホマ大学気象学教室