Semidiurnal Tidal Wind Oscillation at Marcus Island

YUKIHIRO MORI

Earth Science Laboratory, Kagawa University, Kagawa 760 Japan

(Manuscript received 13 October 1983, in final form 18 January 1984)

ABSTRACT

The daily variation of the surface wind at Marcus Island (24°N, 154°E) in the subtropical Pacific area has been investigated with respect to the semidiurnal atmospheric tide. The semidiurnal oscillations of scalar wind speed and vector components of wind have been analyzed harmonically. The phase of the zonal wind component in local time agrees with the observed values at Bermuda and in the Atlantic trades.

Using the Ekman model, the semidiurnal tidal wind oscillation in the planetary boundary layer has been investigated, and an analytic solution has been obtained. In order to fit the theoretical tidal wind oscillation to the observed one, the eddy viscosity K should be smaller than 0.1 $m^2 s^{-1}$. This value of K appears smaller than the representative value in the trades. This suggests the limitation of the simple model.

1. Introduction

A spectrum of long-period fluctuations of the surface wind at Marcus Island (24°N, 154°E) has shown that both diurnal and semidiurnal spectral peaks are small but clearly found (Mori, 1980). From the daily variation of the resultant wind vector, it has been suggested that the daily wind variation seems to be related not to the thermal effect of the island body but to the atmospheric tides.

In the upper atmosphere the tidal wind oscillation is clearly found and many studies have been performed (for a review see Chapman and Rindzen, 1970). Other studies have been presented by Carlson and Hastenrath (1970), Willson (1975), Pedder (1978), and Yoshida and Hirota (1979). Near the surface, on the other hand, the tidal wind oscillation is generally masked by wind variations originating from other causes, and therefore it is difficult to detect, especially over land.

However, at sea the diurnal wind variation originating from other causes may be small, so that here it may be easier to detect the tidal wind oscillation than over land. Surface wind records taken on board ship (or buoy) or at an island in various regions of the Atlantic were analyzed by Kuhlbrodt and Reger (1938), Bartrum (1957), Hoeber (1969) and Prümm (1976). They found that the semidiurnal wind oscillations were closely related to the semidiurnal pressure wave. On the other hand, there are few observational studies of the tidal variation of the surface wind in the Pacific area.

The purpose of the present study is to investigate the daily variation of the surface wind at Marcus Island which lies in the subtropical Pacific area and to examine a relationship between the daily wind variation at this island and the daily march of the pressure wave.

2. Observational results

Eight years of the surface wind data (1970–77) obtained at Minamitori-Shima (Marcus Island) Meteorological Observatory were used in this study. These data are the same as those used in the spectral analysis of surface wind fluctuations (Mori, 1980); details of the data have been presented in that paper. Marcus Island is of coral composition, and its surface is flat. The coastline forms an approximate equilateral triangle ~ 2 km on a side, and the observatory is situated 160 m from the east coastline (see Fig. 4 in Mori, 1980). The elevation of this site is 8 m MSL. The wind data represent 10 min averages at 13 m above the ground. The wind observations were made eight times daily according to Japan Standard Time (JST; the zone time at 135°E). Marcus Island is 19° east from this longitude. In this study, local time is therefore calculated as LT = JST + 1.27 h.

Means of scalar wind speed (S), the east–west (u) and north–south (v) components were calculated from all of the 8 years' data at three-hourly intervals; the results are shown in Fig. 1. The u- and v-components are positive for westerly and southerly winds, respectively. The deviations from the daily mean for each wind component can be statistically regarded as the reflection of the daily wind variations. The daily variation in the mean scalar wind speed (S) is mainly a semidiurnal oscillation with little apparent contribution from a diurnal Fourier component, with its maxima at about 1000 and 2200 LST and its minima at 0400 and 1600. The u- and v-components also have two maxima and two minima, but these semidiurnal oscillations are less uniform with an apparent contribution from a diurnal Fourier component.

The three-hourly mean wind vectors were each di-

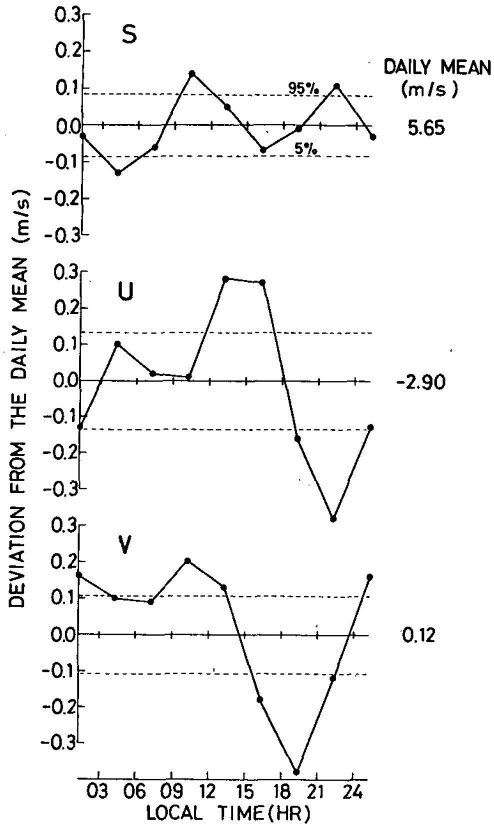

FIG. 1. Resultant daily wind variation at Marcus Island. S—scalar wind speed; u—westerly component; v—southerly component.

vided into a daily mean wind vector (93°, 2.9 m s^{-1}) and an "additional" vector. The directions of the additional wind vectors during daytime and nighttime are opposite to what would be expected from the thermal effect of the island land mass as explained in the previous paper (Mori, 1980). The vectors are small and less than 14% of the daily mean wind vector in magnitude. The direction of the daily mean wind vector is near east so that the daily variation of the scalar wind speed is more closely related to the u-component than the v-component. Namely, when the deviation of u from the daily mean is positive, that of the scalar wind speed is negative and *vice versa*. Kuhlbrodt and Reger (1938) also found a predominantly semidiurnal oscillation of scalar wind speed in the Atlantic trades and suggested that this finding is possibly related to an additional easterly wind component caused by the double diurnal waves of atmospheric pressure.

The resultant daily variations of the scalar wind speed and the vector components of wind are harmonically analyzed. In the case of S, the semidiurnal harmonic has the largest amplitude while in the cases of u and v, the diurnal harmonics are larger than the semidiurnal harmonics in amplitude as expected from Fig. 1. However, in order to investigate a relationship between the daily wind variation and the semidiurnal atmospheric tide, the semidiurnal harmonic components are analyzed in the present study. The results are shown in (I) of Table 1. The semidiurnal harmonic components of S, u and v are also calculated from the resultant daily wind variations for each year. The means of 8 determinations of amplitudes and phases are shown in (II) of Table 1 with the probable errors of these means. Two determinations of (I) and (II) agree closely. The probable errors of the means of amplitude and phase variables are very small for each component of S, u and v. The phase difference between u and v is 83° and is near $\pi/2$ rad. The phase difference between S and u is 150° and is near π rad. The first maxima of u, v and S occur at 3.5, 0.8 and 10.0 h LT, respectively.

TABLE 1. Semidiurnal harmonic components of the mean daily variations of the wind at Marcus Island. (I) is calculated from the 8-year mean daily wind variations (Fig. 1). (II) shows the means of the 8 harmonic determinations of S, u and v for each year. The probable errors (P.E.) of the means of amplitudes and phases are presented in parentheses. The harmonic components are fitted to the form $A \sin(2\omega_0 T + \alpha)$, where T is in local time and ω_0 is angular velocity of the earth's rotation.

	I		II			
	A (m s^{-1})	α (deg)	A (m s^{-1})	P.E.	α (deg)	P.E.
S	0.12	131	0.12	(0.01)	133	(4)
u	0.20	344	0.20	(0.01)	344	(2)
v	0.15	67	0.15	(0.01)	66	(3)

Prümm (1976) has summarized the daily wind variations in the tropical Atlantic obtained from the three Atlantic *Meteor* expeditions: the *Meteor* Expedition 1925–27, the Atlantic Expedition 1965 (IQSY) and the Atlantic Trade Wind Experiment (ATEX) 1969. His results for semidiurnal wind oscillations are given in Table 2 with the results obtained from Bermuda (Bartrum, 1957) and Marcus Island. The time of the first maximum of u at Marcus Island agrees well with

TABLE 2. Amplitudes (A) and times of the first maxima (α) of the semidiurnal wind oscillations in the Atlantic trade wind region (Prümm, 1976) and at Bermuda (Bartrum, 1957) and at Marcus Island.

	NE-trades*		SE-trades*			
	ATEX 1969	*Meteor* 1925–27	ISQY 1965	*Meteor* 1925–27	Bermuda**	Marcus
S A (m s^{-1})	0.21	0.17	0.22	0.24	0.17	0.12
$\alpha(h)$	9.4	10.0	9.1	9.3	0.8	10.6
u A (m s^{-1})	0.23	0.32	0.22	0.23	0.23	0.20
$\alpha(h)$	3.6	5.7	3.5	3.7	3.9	3.5
v A (m s^{-1})	0.07	0.31	0.10	0.15	0.28	0.15
$\alpha(h)$	4.2	1.4	7.7	9.1	0.4	0.8

* After Prümm (1976).
** After Bartrum (1957).

those in the Atlantic trades and at Bermuda, except the value of *Meteor* 1925–27 in the northeast trades. The time of the first maximum of v at Marcus Island agrees with that at Bermuda to within 0.4 h, but does not agree with the values of the Atlantic trades. The times of the first maxima in v in the three Atlantic expeditions are different from each other and do not agree with the value estimated by frictionless theory. As suggested by Prümm (1976), these discrepancies could be the result of sampling errors in the estimated semidiurnal variation of v, due to the relatively short time series available from these experiments.

Except for Bermuda, the times of the first maxima in S almost agree. As mentioned before, it is considered that in a prevailing easterly wind region a semidiurnal oscillation of scalar wind speed is related to an additional easterly wind component forced by the semidiurnal variation in surface pressure. The phases of the semidiurnal components in S and u are different by 6 h. This is consistent with the relationship mentioned above. At Bermuda the time of the first maximum in S agrees with that in v.

The previous results for Marcus Island are based on averaging the daily variation over the entire eight-year dataset. Fig. 2 shows the amplitudes and phases for the daily variation averaged over all data within individual months (for details see Mori, 1982). The times (LT) of the first maxima are 0900–1200 for S and 0000–0200 for u and 0300–0400 for v. The amounts of monthly scatter in phase and magnitude for each wind component are relatively small. This suggests that the semidiurnal wind oscillation exists throughout the year with almost the same amplitude and phase.

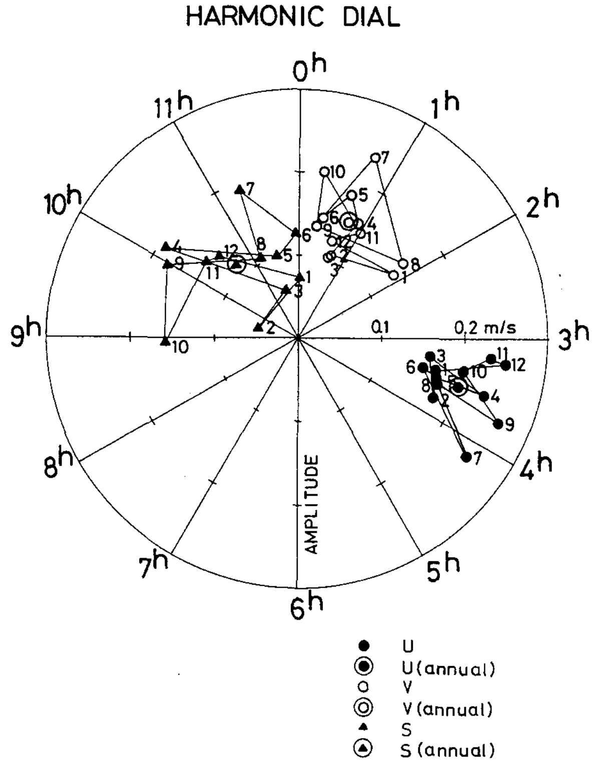

FIG. 2. Harmonic dial for the semidiurnal oscillation of the wind at Marcus Island (Numbers denote months): S (triangles), u-component (solid circles), v-component (open circles). Encircled triangle, solid and open circle indicate annual mean for S, u- and v-components, respectively.

3. Theoretical approach

Analytical solutions of the equation of motion caused by the tidal wave for frictionless flow have been presented by Gold (1910), Bartels (1928) and others. However the frictional force can not be neglected in the planetary boundary layer. Gold also attempted to allow for frictional force and computed amplitudes and phases of the diurnal and semidiurnal tidal winds on the assumption that the frictional force is proportional and opposite to the motion and found that the effect of friction is to change both amplitude and phase of the motion.

Harris (1963) and Harris *et al.* (1966) have presented an analytical solution of tidal air motion on the assumption of the constant eddy viscosity K. Harris obtained his solution using a perturbation method. Under the condition he used, the amplitudes of u and v become equal. Therefore, his solution does not explain the observed daily variation at low latitudes, where the amplitude of tidal variation in v is found to be smaller than that in u.

Lettau (1974) has made a theoretical study of the semidiurnal tidal wind oscillation in the friction layer, using a more realistic model in which the eddy viscosity K depends both on height and time. He has compared his theoretical results with the observation obtained during the *Meteor* experiment (which was made near the equator) and found a good agreement. However, in his model the Coriolis force is neglected, so his results can not be compared with the observations taken at regions except near the equator.

In the present study a theoretical tidal wind motion for the friction layer is obtained at latitudes lower than 30°N (except on the equator) in the Northern Hemisphere. For a neutral, incompressible and horizontal homogeneous atmosphere with constant eddy viscosity K, the equations of motion take the form

$$\frac{\partial u}{\partial t} - fv - K\frac{\partial^2 u}{\partial z^2} = -\frac{1}{\rho}\frac{\partial p}{\partial x}, \tag{1}$$

$$\frac{\partial v}{\partial t} + fu - K\frac{\partial^2 v}{\partial z^2} = -\frac{1}{\rho}\frac{\partial p}{\partial y}, \tag{2}$$

where f is the Coriolis parameter, p pressure, ρ the density of air (constant). The Ekman model—K independent of height and time—seems to be too simple, but in this case we can get an analytical solution. The simple Ekman model is therefore useful in improving our understanding of the response of the planetary boundary layer to atmospheric tidal forcing.

The terms of the pressure gradient force in (1) and (2) are replaced as follows:

$$-\frac{1}{\rho}\frac{\partial p}{\partial x} = -fv_g, \tag{3}$$

$$-\frac{1}{\rho}\frac{\partial p}{\partial y} = fu_g, \tag{4}$$

where u_g and v_g are the components of the geostrophic wind. Then, the time changes of the pressure gradient force are represented by those of u_g and v_g.

The semidiurnal pressure oscillation can be represented by the following empirical formula (Haurwitz and Cowley, 1973):

$$S_2(P) = P_s \sin^3\theta \sin(2\omega_0 T + \sigma), \tag{5}$$

where θ is colatitude, P_s = 116.1 Pa, σ = 159°, T in local time. From this formula the time changes of u_g and v_g are written as

$$u_g = a \sin(2\omega_0 T + \sigma), \tag{6}$$

$$v_g = b \cos(2\omega_0 T + \sigma), \tag{7}$$

where

$$a = \frac{3P_s \sin^2\theta \cos\theta}{f\rho R}, \quad b = \frac{2P_s \sin^2\theta}{f\rho R}$$

and R is radius of the earth.

By using the following notations

$$\left.\begin{aligned} A &= \frac{a-b}{2}\frac{f}{f+2\omega_0}, \quad & B &= \frac{a+b}{2}\frac{f}{f-2\omega_0} \\ \alpha &= \left(\frac{2\omega_0+f}{2K}\right)^{1/2}, \quad & \beta &= \left(\frac{2\omega_0-f}{2K}\right)^{1/2} \\ a_1 &= 1 - e^{-\alpha z}\cos\alpha z, \quad & a_2 &= e^{-\alpha z}\sin\alpha z \\ b_1 &= 1 - e^{-\beta z}\cos\beta z, \quad & b_2 &= -e^{-\beta z}\sin\beta z \end{aligned}\right\},$$

the solutions for u and v are written as follows (see Appendix),

$$u(z, T) = U_2 \sin(2\omega_0 T + \phi_u), \tag{8}$$

$$v(z, T) = V_2 \sin(2\omega_0 T + \phi_v), \tag{9}$$

where

$$U_2 = [(Aa_1 + Bb_1)^2 + (Aa_2 - Bb_2)^2]^{1/2},$$

$$V_2 = [(Aa_2 + Bb_2)^2 + (Aa_1 - Bb_1)^2]^{1/2},$$

$$\phi_u = -\tan^{-1}\frac{Aa_1 + Bb_1}{Aa_2 - Bb_2} + 90° + \sigma,$$

$$\phi_v = -\tan^{-1}\frac{Aa_2 + Bb_2}{Bb_1 - Aa_1} + 90° + \sigma.$$

Using the values of the latitude and the air density corresponding to those at Marcus Island, the amplitudes and phases for various values of K are calculated and shown in Fig. 3. This figure shows phase leads and reduced amplitudes near the surface, relative to

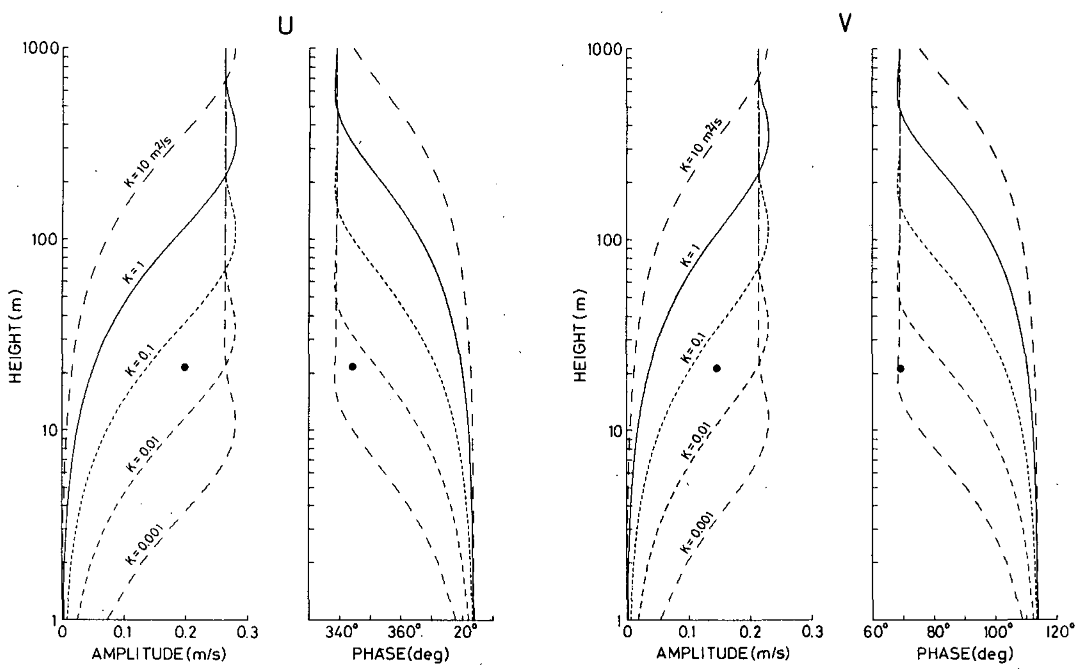

FIG. 3. Theoretical amplitudes and phases for the semidiurnal components of u and v. Solid circles indicate the observed values at Marcus Island.

values at $z > 100$ m. The observed values at Marcus Island are plotted on the figure. In order to fit the theoretical value of the amplitude to the observed one, the value of K should be smaller than 0.1 $m^2 s^{-1}$. The phases of u and v almost coincide with the value of the frictionless theory and in order to fit the theoretical phase to the observed one the value of K should be smaller than 0.01 $m^2 s^{-1}$. These results suggest the limitation of the simple model, but confirm that the observed semidiurnal wind oscillation at Marcus Island is caused by the semidiurnal atmospheric tide.

4. Concluding remarks

The first maxima of the semidiurnal oscillations in u, v components and the scalar wind speed (S) at Marcus Island occur at 3.5, 0.8 and 10.5 h LT, respectively. The time of the first maximum in u in LT agrees well with those in the Atlantic trades.

Using the Ekman model (K = constant), the semidiurnal tidal wind oscillation in the planetary boundary layer has been investigated. In order to fit the theoretical results to the observed one, K should be smaller than 0.1 $m^2 s^{-1}$ for amplitudes and 0.01 $m^2 s^{-1}$ for phases, respectively. This value of K appears one (or more) order magnitude smaller than the representative value of K in the trade wind. This leads to the same conclusion as Harris (1963) that the Ekman model does not produce realistic results, especially near ground level. This may have originated from the unrealistic assumption that K does not depend on height nor time (Lettau, 1974), and suggests the limitation of the simple analytic model.

Acknowledgments. I would like to express my thanks to Professor Y. Mitsuta, Kyoto University, for his valuable suggestions. Thanks should be extended to the Japan Meteorological Agency for making the data tapes available. I am also greatly indebted to the reviewer for his comments which have led to improvements in the presentation of the revised paper. The computations were made at the Computer Center of Kagawa University.

APPENDIX

Analytical Solution

Mori (1981) has obtained an analytic solution of the response of the planetary boundary layer to time varying pressure gradient force. The geostrophic winds corresponding to pressure gradient force change with time as represented by

$$\left.\begin{aligned} u_g &= u_{g0} + a\cos\omega t \\ v_g &= b\sin\omega t \end{aligned}\right\},$$

where u_{g0}, a, b, and ω are constants.

Under the boundary conditions

$$\left.\begin{aligned} u(0, t) &= 0 \\ v(0, t) &= 0 \end{aligned}\right\}$$

and the initial conditions

$$\left.\begin{aligned} u(z, 0) &= 0 \\ v(z, 0) &= 0 \end{aligned}\right\},$$

the solution obtained has the form

$$\begin{aligned} u + iv = {} & \frac{a-b}{2}\frac{f}{f-\omega}\exp(-i\omega t)[1 - F(f-\omega)] \\ & + \frac{a-b}{2}\frac{f}{f+\omega}\exp(i\omega t)[1 - F(f+\omega)] \\ & + \left[\frac{(b\omega - af)f}{f^2-\omega^2} - u_{g0}\right]\exp(-ift) \\ & \times\left[1 - \operatorname{erfc}\frac{z}{(4Kt)^{1/2}}\right] + u_{g0}[1 - F(f)], \end{aligned}$$

where

$$\begin{aligned} F(x) = {} & \frac{1}{2}\exp\left[(1+i)z\left(\frac{x}{2K}\right)^{1/2}\right]\operatorname{erfc}\left[\frac{z}{(4Kt)^{1/2}}\right. \\ & \left. + (1+i)\left(\frac{xt}{2}\right)^{1/2}\right] + \frac{1}{2}\exp\left[-(1+i)z\left(\frac{x}{2K}\right)^{1/2}\right] \\ & \times\operatorname{erfc}\left[\frac{z}{(4Kt)^{1/2}} - (1+i)\left(\frac{xt}{2}\right)^{1/2}\right], \end{aligned}$$

and erfc is the complementary error function. When $x < 0$, $F(x)$ is written as

$$\begin{aligned} F(x) = {} & \frac{1}{2}\exp\left[-(1+i)z\left(-\frac{x}{2K}\right)^{1/2}\right]\operatorname{erfc}\left[\frac{z}{(4Kt)^{1/2}}\right. \\ & \left. - (1-i)\left(-\frac{xt}{2}\right)^{1/2}\right] + \frac{1}{2}\exp\left[(1-i)z\left(-\frac{x}{2K}\right)^{1/2}\right] \\ & \times\operatorname{erfc}\left[\frac{z}{(4Kt)^{1/2}} + (1-i)\left(-\frac{xt}{2}\right)^{1/2}\right]. \end{aligned}$$

For latitudes lower than 30°N in the Northern Hemisphere, in the case of the semidiurnal tidal wave,

$$f > 0, \quad \omega = -2\omega_0$$

so that,

$$f - \omega > 0, \quad f + \omega < 0.$$

We let $u_{g0} = 0$, and if t approach infinity, the solution in this case approaches the following form:

$$\begin{aligned} u + iv = {} & A\exp(-i\omega t)\left\{1 - \exp\left[-(1+i)z\left(\frac{f-\omega}{2K}\right)^{1/2}\right]\right\} \\ & + B\exp(i\omega t)\left\{1 - \exp\left[-(1-i)z\left(-\frac{f+\omega}{2K}\right)^{1/2}\right]\right\}, \end{aligned}$$

where

$$A = \frac{a-b}{2}\frac{f}{f-\omega}, \quad B = \frac{a+b}{2}\frac{f}{f+\omega}.$$

REFERENCES

Bartels, J., 1928: Gezeitenschwingungen der Atmosphäre. *Wien-Harms Handbuch der Experimental-Physik, Geophysik,* Vol. 1, Akademische Verlagsgesellschaft, 163–210.

Bartrum, P. C., 1957: The diurnal variation of surface wind and pressure at Bermuda. *Meteor. Mag.,* **86,** 296–301.

Carlson, Jr., G. C., and S. Hastenrath, 1970: Diurnal variation of wind, pressure, and temperature in the troposphere and stratosphere over Eniwetok. *Mon. Wea. Rev.,* **98,** 408–416.

Chapman, S., and R. S. Lindzen, 1970: *Atmospheric Tides.* Reidel, 200 pp.

Gold, E., 1910: The relationship between periodic variations of pressure, temperature, and wind in the atmosphere. *Philos. Mag. London,* 6th Ser., **19,** 26–49 and 448.

Harris, M. F., 1963: Semidiurnal tidal motions in the friction layer. *Mon. Wea. Rev.,* **91,** 557–565.

——, F. G. Finger and S. Teweles, 1966: Frictional and thermal influences in the solar semidiurnal tide. *Mon. Wea. Rev.,* **94,** 427–447.

Haurwitz, B., and A. D. Cowley, 1973: The diurnal and semidiurnnalbarometric oscillations, global distribution and annual variation. *Pure Appl. Geophys.,* **102,** 193–222.

Hoeber, H., 1969: Wind-, Temperatur- und Feuchteprofile in der wassernahen Luftschicht uber dem equatorialen Atlantik. *"Meteor" Forschungsergeb.,* Reihe B: Meteorologie und Aeronomie, **3,** 1–25. (Gebrüder Borntraeger, 1 Berlin 38 · 7 Stuttgart 1)

Kuhlbrodt, E., and J. Reger, 1938: Die meteorologischen Beobachtungen: Methoden, Beobachtungsmaterial und Ergebnisse. *Wissenschaftliche Ergebnisse der Deutschen Atlantischen Expedition auf dem Forschungs- und Vermessungsschiff 'Meteor,' 1925–1927,* **13B,** 263–323. [available from the British Library Lending Division, Boston Spa, Wetherby, West Yorkshire, United Kingdom].

Lettau, H., 1974: Semi-diurnal wind variation in the friction layer above the tropical ocean. *Bound. Layer Meteor.,* **6,** 13–33.

Mori, Y., 1980: Spectrum of long-period fluctuations of the surface wind at Marcus Island. *Mon. Wea. Rev.,* **108,** 1456–1461.

——, 1981: Analytic solution of the planetary boundary layer containing time-dependent terms. *Mem. Fac. Educ.,* Kagawa University, II, **31,** 233–238. [available from the Faculty of Education, Kagawa University, Takamatsu, Kagawa 760, Japan].

——, 1982: On daily variation of surface wind at Marcus Island (in Japanese with English abstract). *Mem. Fac. Educ., Kagawa Univ.,* II, **32,** 37–48. [available from the above address].

Pedder, M. A., 1978: Diurnal and semidiurnal variations in the A/B scale-averaged wind fields during Phase III of GATE. *Mon. Wea. Rev.,* **106,** 782–788.

Prümm, D., 1974: Height dependence of diurnal variations of wind velocity and water temperature near the air-sea interface of the tropical Atlantic. *Bound. Layer Meteor.,* **6,** 341–347.

——, 1976: Note on the diurnal variations of air pressure and wind in the Atlantic surface layer. *Meteor Forschungsergeb.,* Reihe B: Meteorologie und Aeronomie, **11,** 94–101. (Gebrüder Borntraeger, 1 Berlin 38 · 7 Stuttgart 1)

Willson, M. A. G., 1975: Atmospheric tidal motions over Australia below 20 kilometers. *Mon. Wea. Rev.,* **103,** 1110–1120.

Yoshida, Y., and I. Hirota, 1979: Diurnal wind variation in the troposphere and lower stratosphere over Japan. *J. Meteor. Soc. Japan,* **57,** 29–38.