A Study on Climatological Aspects of Winds in Japan. Part I: Mean Wind Fields and Annual Variations of Winds

YUKIHIRO MORI

Earth Science Laboratory, Kagawa University, Takamatsu, Japan

(Manuscript received 8 April 1987, in final form 1 September 1987)

ABSTRACT

Using the winds in Japan as an example, the validity of the vectorial treatment of the surface wind in climatological investigations has been demonstrated, and the expressions for climatological mean and variability of the wind have been reviewed. The annual resultant surface winds tend to be westerly at latitudes higher than 30° and easterly at lower latitudes. At lower latitudes, the mean surface winds and the mean 850 mb winds are almost opposite to each other in direction at times.

Climatological mean wind directions according to different definitions have been investigated for the surface wind. The means of wind direction agree with the directions of the vector mean wind within 30° where the magnitudes of the vector mean wind are larger than 1.5 m s^{-1}. The relationships between the two measures of the constancy of the wind are investigated.

1. Introduction

The mean fields of the wind are important to know in order to understand the behavior of the atmosphere. Since the wind is a vector quantity which has both magnitude and direction, measurements and statistics of the wind are more complicated than those of other scalar meteorological quantities. Fundamental subjects in wind statistics have been discussed for short time observations in Mori (1986b, 1987).

Climatological aspects of the winds in Japan, which lies in the Asian monsoon area, have been studied by Yoshino (1966), Kawamura (1977) and others. However, in these studies, vector mean wind fields have hardly been investigated. The author, however, has investigated climatological aspects of the wind in Japan: the vector mean wind fields (Mori, 1981a,b), the daily variation of the wind (Mori, 1982, 1983a,c,d) and the annual variation and constancy of the wind (Mori, 1983b, 1986a).

The purpose of this paper is to summarize the climatological mean wind fields and the annual variations of the wind in Japan, and to discuss the expressions for a climatological mean and variability of the wind.

2. Data and analysis

Investigation of mean wind fields requires not only statistics of scalar wind speed and wind direction but also statistics of the winds as vector quantities. In the case of the upper wind, the means of the wind are usually calculated for the east–west (u) and north–south (v) components. In the case of the surface wind, wind speed and wind direction are treated separately and the means of the wind components are hardly calculated in standard wind statistics. This may be derived partly from the traditional observing techniques for the wind; i.e., in the case of the upper wind, wind vectors are measured from the movement of a balloon, while in the case of the surface wind, wind direction and wind speed are measured from different apparatuses. A more fundamental problem, however, is treatment of the statistics of the surface wind.

In the treatment of climatological means of the surface wind, it seems that treatment of the wind as a natural vector quantity was more prevalent in historical times than today. For example, Coffin (1875) showed the effect of combining the element of wind speed in computing the mean direction. Davis (1893) mentioned that "It must be understood that the mean direction of the wind is a resultant based upon all individual observations and many years ago, meteorologists discussed the question as to how this resultant could best be computed." In Japan the resultant winds once were calculated for each month in the routine wind statistics by the meteorological office, but today, mean scalar wind speeds and prevailing wind directions only are calculated for each month in routine statistics, and the resultant winds are not calculated.

In recent years, the large number of surface wind records in Japan have been collected and compiled on magnetic tapes by the Japan Meteorological Agency (JMA). This makes it possible to investigate compre-

---

Corresponding author address: Dr. Yukihiro Mori, Earth Science Laboratory, Kagawa University, Takamatsu 760, Japan.

hensively the climatological mean wind field and other wind statistics throughout Japan.

The magnetic tapes of the JMA used in this study consist of wind records covering the period 1967–77 (11 yr) at 152 meteorological observatories in Japan. The routine wind observations at these sites were taken at 3 h intervals with each value representing a 10 min average at a height of about 15–20 m above the ground. By using this dataset, monthly mean wind vectors were calculated for all sites and the results were tabulated in Mori (1981a).

In order to compare the surface wind field with the upper wind field, the resultant winds at the 850 mb level (about 1500 m height) have been constructed by using aerological data (JMA, 1971, 1976) for the 10 yr period (1966–75). This period almost coincides with the one for the surface wind data analyzed here. It is assumed that the 850 mb wind represents the wind at the upper part of or just above the planetary boundary layer (PBL).

3. Mean wind fields in Japan

A map of Japan is shown in Fig. 1. Japan consists of a long island chain extending along the Pacific coast of the Asian Continent. It includes four main islands, Hokkaidō, Honshū, Shikoku and Kyūshū, together with many smaller islands. The smaller islands extending at latitudes lower than about 30°N are called the Ryūkyū islands. The locations of all of JMA's ra-

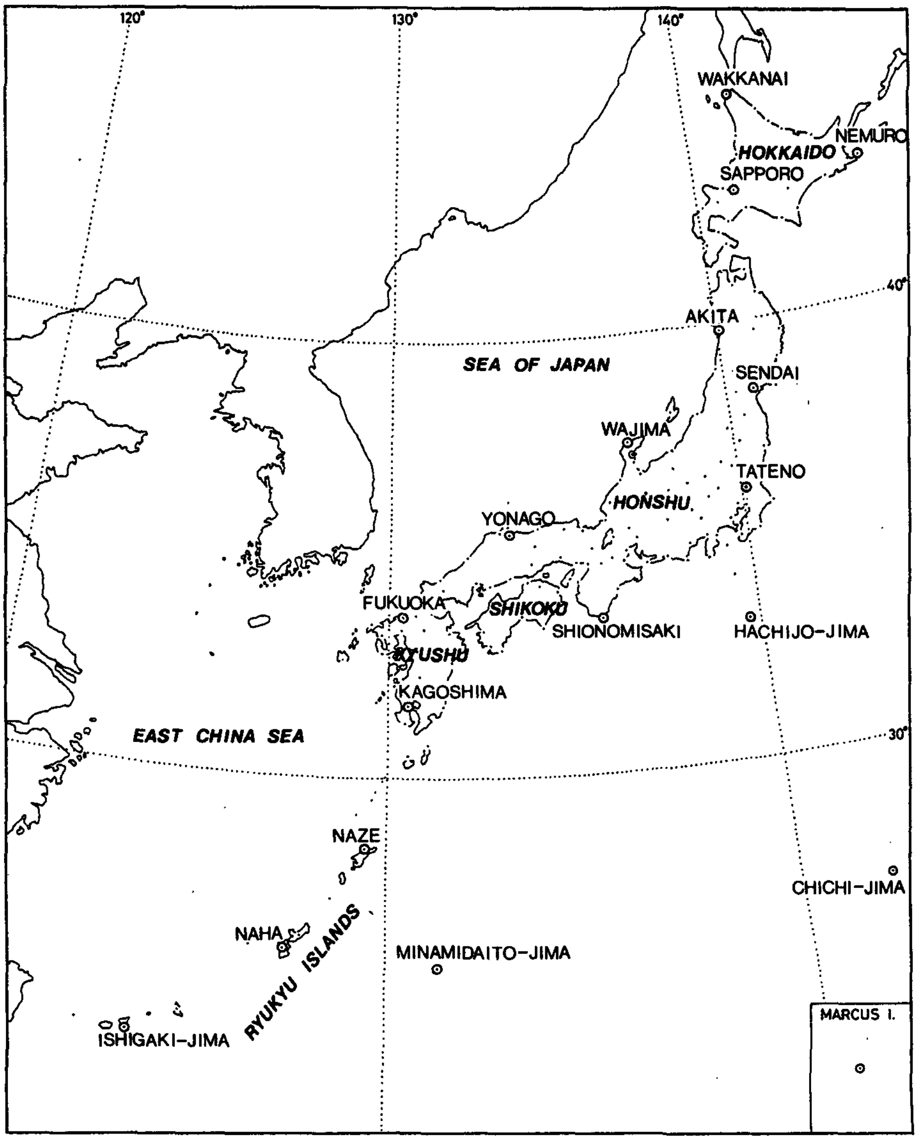

FIG. 1. A map of Japan. Open circles indicate JMA radiosonde sites. Marcus Island is located at 24°N, 154°E.

diosonde sites are also shown in this figure. The 850 mb winds and the surface winds throughout this area were analyzed.

a. Annual mean wind fields and annual variations of winds in Japan

The annual mean vectors of the surface wind are shown in Fig. 2. The surface wind pattern changes significantly at a latitude of about 30°N. The resultant surface winds tend to be westerly or northwesterly at higher latitudes and easterly at lower latitudes. As will be shown in Mori (1987b, Part II), the resultant 850 mb winds are westerly almost all over Japan. Thus on the Ryūkyū islands, the resultant surface winds and the corresponding resultant 850 mb winds are almost opposite to each other in direction.

The monthly mean vectors of the surface and 850 mb winds at the radiosonde sites are shown in Fig. 3. The annual change pattern for the 850 mb wind varies considerably at a latitude of about 30°N. At higher latitudes, the *u*-components of the monthly mean 850 mb wind vectors are almost westerly throughout the year. The magnitudes of the vectors show large annual changes, with their maxima in winter and with their minima in summer. The tips of the monthly mean wind vector change in an eight-shaped path with clockwise rotations in the cold season and counterclockwise rotations in the warm one. The loops in the cold season are larger at higher latitudes (Wakkanai, Sapporo and Nemuro), but these become smaller toward lower latitudes.

On the Ryūkyū islands, the monthly mean 850 mb wind vectors turn counterclockwise during the year and

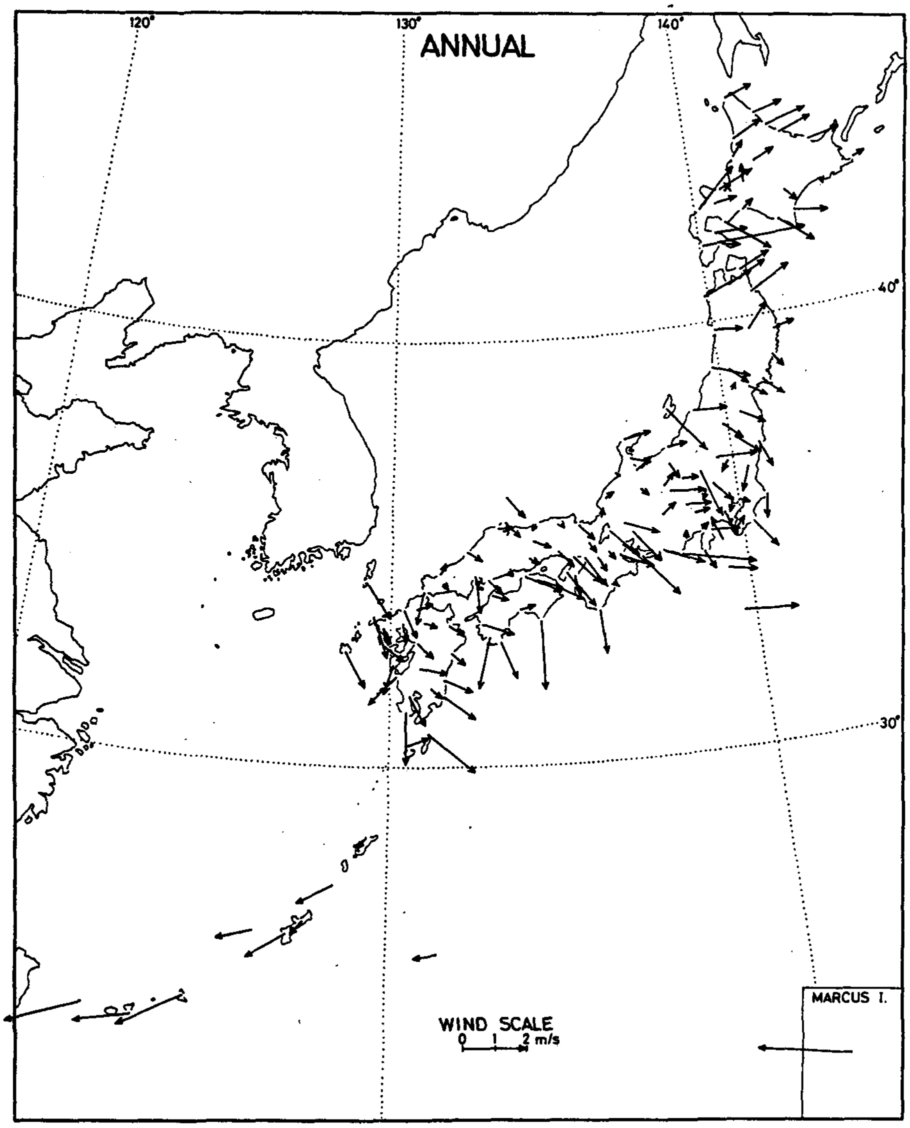

FIG. 2. Annual mean surface wind vectors.

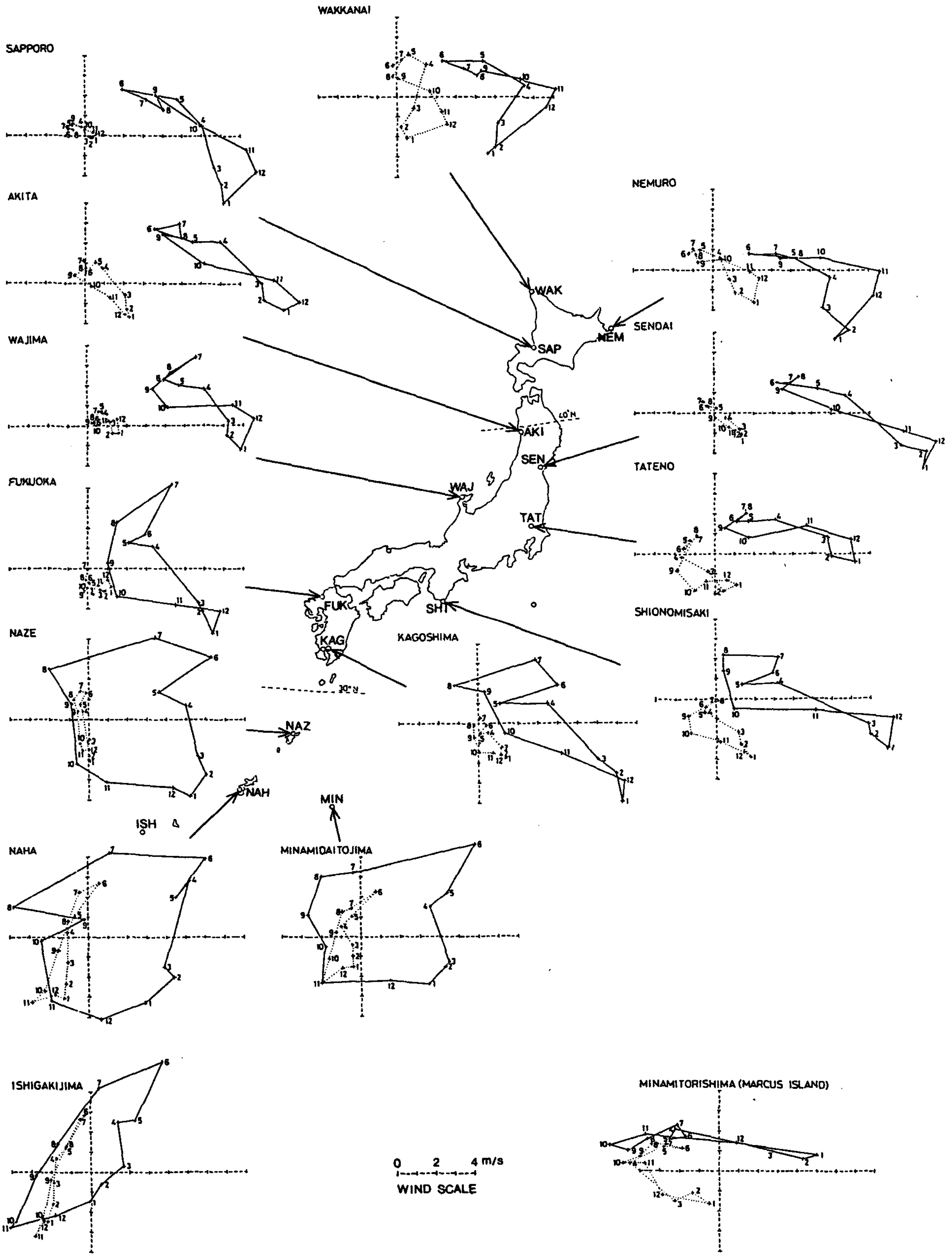

FIG. 3. Monthly mean vectors for the surface and 850 mb winds. Crosses denote the ends of the mean vectors for each month. Solid lines represent the 850 mb winds and dotted lines the surface winds. Numbers denote months.

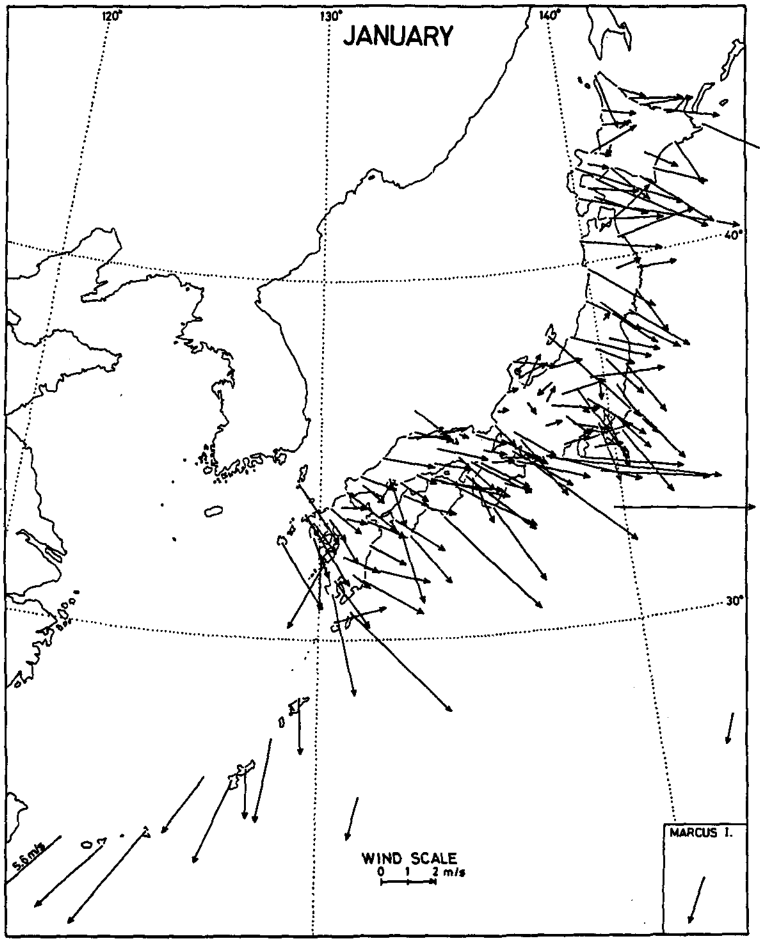

FIG. 4. Mean surface wind vectors: (a) January; (b) July.

the tips of the vector describe a single loop. The loops for Naze, Naha and Minamidaito-jima are roughly circular. The loop for Ishigaki-jima is an ellipsoid which takes its longer axis in the direction of northeast–southwest, and is different in shape from the loops for the other three sites in the Ryūkyū islands.

At Marcus Island (Minamitori-shima in Japanese; 24°N, 154°E), the tip of the monthly mean 850 mb wind vector changes linearly during the year. The *u*-components are westerly from December to March and easterly from April to November. The *v*-components are small and southerly throughout the year. In the case of the surface wind, the *u*-components of the monthly mean wind are easterly throughout the year in striking contrast to the upper wind. The tip of the vector changes in an arc-shape pass. Then, the *u*-component shows semiannual variation and the *v*-component shows annual variation. This result agrees with that of a spectral analysis of long-period fluctuation of the surface wind at this island (Mori, 1980).

At higher latitudes, the shapes described by the tips of the monthly mean surface wind vectors are similar to those for the corresponding 850 mb winds, for example Wakkanai and Nemuro. However, the westerly components of the monthly mean surface wind vectors are generally small.

On the Ryūkyū islands, the tips of the monthly mean surface wind vectors change linearly from south to north, and these patterns are quite different from those for the corresponding 850 mb winds. At these sites, the *v*-components of the resultant surface winds show large annual variations; these are southerly in summer and are northerly in winter. On the other hand, the magnitudes of the annual changes of the *u*-components are relatively small. Even when the resultant 850 mb winds show large westerly components, the resultant surface winds are easterly or only slightly westerly. Then, a large difference between the mean 850 mb and surface wind vectors occurs in the cold season. Sometimes the directions of the mean surface wind vectors and the corresponding mean 850 mb wind vectors are nearly opposite to each other in the Ryūkyū islands and Marcus Island. This can not be explained by the effect of the surface drag and the Coriolis force only.

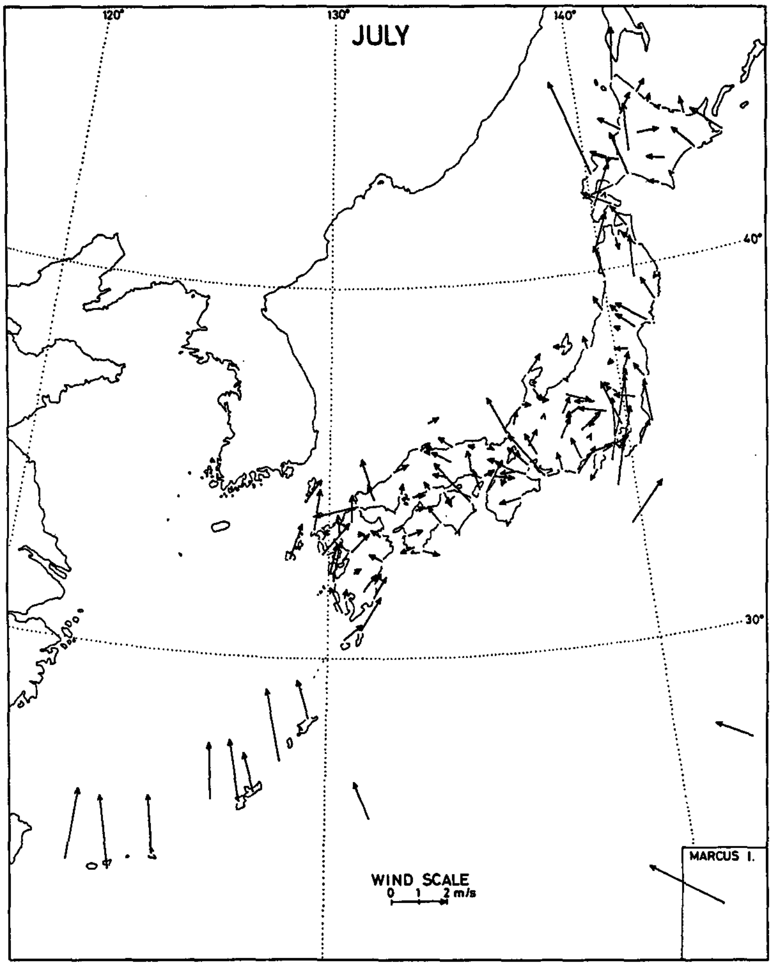

FIG. 4. (*Continued*)

Sheppard et al. (1952) and Gray and Mendenhall (1973) have found that the observed wind profiles in the PBL are strongly affected by the thermal wind. Theoretical studies of wind profiles in the baroclinic PBL have been made by many researchers (see MacKay, 1971; Hoxit, 1974). Theoretical and observational studies suggest that the thermal wind causes a large angle between the upper wind and the surface wind. The thermal winds and their contributions to the wind in the PBL will be discussed in Mori (1987b, Part II).

Following meteorological convention, the periods chosen for the computation of the means for all sites are the two extreme months of January and July. The vector means of the surface wind for January and July are shown in Fig. 4a, b. Those for the 850 mb wind will be shown in Mori (1987b, Part II).

In January (Fig. 4a) the directions of the resultant surface wind are roughly WNW-NW at latitudes higher than 30°N, and N-NE at the lower latitudes. Thus, the resultant surface wind changes significantly with latitude. On the Ryūkyū islands, the directions of the resultant surface wind are relatively uniform with a gradual change from N to NE toward lower latitudes. In the main islands, the directions of the resultant surface wind vary widely.

In July (Fig. 4b) in the main islands, the directions of the resultant surface winds are very scattered and the magnitudes of the vectors are generally smaller than those in January. This is caused by the fact that the general wind is weak in this month and the local winds affect the resultant winds considerably. The resultant surface winds on the Ryūkyū islands are opposite in direction to those in January.

Mintz and Dean (1952) investigated the mean wind fields in January and July all over the world. They obtained the wind fields by using the wind direction data only, except for North America. Their results for the area around Japan agree roughly with those of the present study.

The magnitudes of the annual variation of the wind were also investigated. Harmonically analyzing the monthly means of the u- and v-components of the surface wind, the annual ellipsoids of the wind were ob-

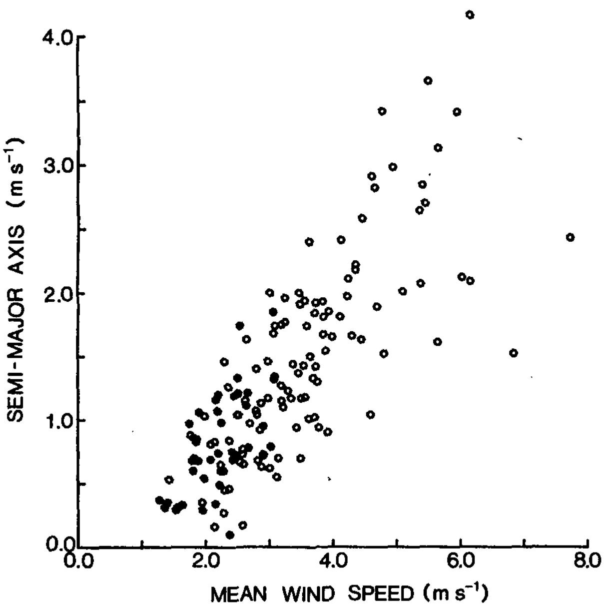

FIG. 5. The relationship between the length of the semimajor axis of annual ellipsoid and the annual mean scalar wind speed. Solid circles indicate stations more than 20 km inland from the coast.

tained by using the same method as used in obtaining the daily ellipsoid (O'Brien, 1974).

In most sites, the annual ellipsoids have very flat shapes and show counterclockwise rotation. Then, let the length of the semi-major axis be a measure of magnitude of the annual variation of the monthly mean wind vector. The relationship between the length of the semi-major axis and the annual mean scalar wind speed is shown in Fig. 5. The magnitude of the annual variation of the vector wind increases with the increase of the annual mean scalar wind speed. Thus, where the annual mean scalar wind speed is high, the magnitudes of annual variations of the wind vector are large.

The monthly means of scalar wind speed were also analyzed harmonically and the amplitudes of the annual variation of scalar wind speed, A_s, were obtained. The relationship between the value of A_s and the annual mean scalar wind speed is also shown in Fig. 6. The large values of A_s are found where annual mean scalar wind speeds are high, as expected. However, though the annual mean wind speeds are high, some sites show only small values of A_s. Most of the sites where the values of A_s are quite small are near the coasts of the Pacific or the Seto Inland Sea which lies between Honshū and Shikoku. These sites are leeward of the mountains in prevailing winter winds. Thus, the value of A_s is influenced by surrounding topography and the magnitude of the annual mean scalar wind speed cannot be considered as a measure of A_s. Figure 6 suggests that the values of A_s do not exceed about half of the magnitudes of the annual mean wind speeds. A more detailed discussion of the annual variation of the wind in Japan has been presented in Mori (1986a).

b. *Mean wind direction and constancy of the wind*

1) THEORETICAL BASIS

The wind is a vector quantity, so, as mentioned previously, it is natural to define the direction of the resultant wind as a mean wind direction. A mean of the wind direction can be obtained by the vector addition of the branches (more exactly the lengths of petals) of the wind rose, the length of each branch of the rose being proportional to the frequency with which the wind come from the given direction (Mintz and Dean, 1952). This definition of mean wind direction is statistically the same as the mean angle defined by Mardia (1972) (see Mori, 1987a).

Mardia (1972) has made a comprehensive and theoretical study of angular data. He defines the mean direction Da and the circular standard deviation of direction σ_d as follows. Let P_i be the point on the circumference of the unit circle corresponding to the angle D_i and O be the center of the circle. Then the mean direction Da is defined to be the direction of the resultant of the unit vectors $\overline{OP_i}$, $i = 1, \cdots, n$. Thus,

$$Da = \tan^{-1}(Sa/Ca) \qquad (1)$$

where the average value of $\cos D_i$ is defined as

$$Ca = n^{-1} \sum \cos D_i \qquad (2)$$

and the average value of $\sin D_i$ as

$$Sa = n^{-1} \sum \sin D_i. \qquad (3)$$

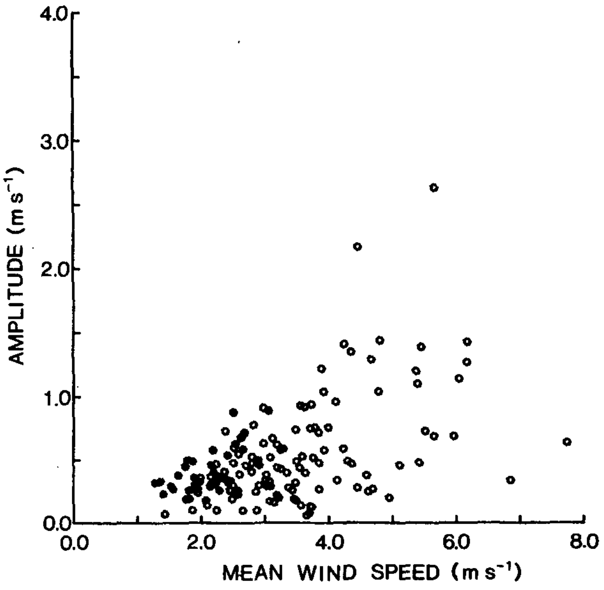

FIG. 6. The relationship between the amplitude of annual variation of scalar wind speed, A_s, and the annual mean wind speed. Solid circles indicate stations more than 20 km inland from the coast.

The standard deviation of direction in radian measure is

$$\sigma_{dm} = (-2\ \ln R)^{1/2} \tag{4}$$

where

$$R = (Sa^2 + Ca^2)^{1/2} = Cr. \tag{5}$$

The *Cr* term will be discussed later.

Equation (4) is derived under the assumption that the values of D_i have a normal distribution. In actual climatological wind data, wind directions cannot be expected to be distributed according to a normal law. However, from (4) or (5) we can obtain a measure of the scatter of wind direction distribution. Johnson and Kalma (1986) used the mean wind direction *Da* and circular variance S (=1 − R) defined by Mardia in their climatological investigation of the wind in Australia.

As mentioned before, the means of the wind direction at each site are obtained by the vector addition of the branches of the wind rose. The length of the composite branch, *Cr*, is statistically equal to Mardia's *R* (Mori, 1987a). Then, *Cr* represents the constancy of the wind.

The magnitude of the vector mean wind, *Vv*, is less than the mean of scalar wind speed, *Va*, because wind direction is not constant. Thus, the ratio of the two

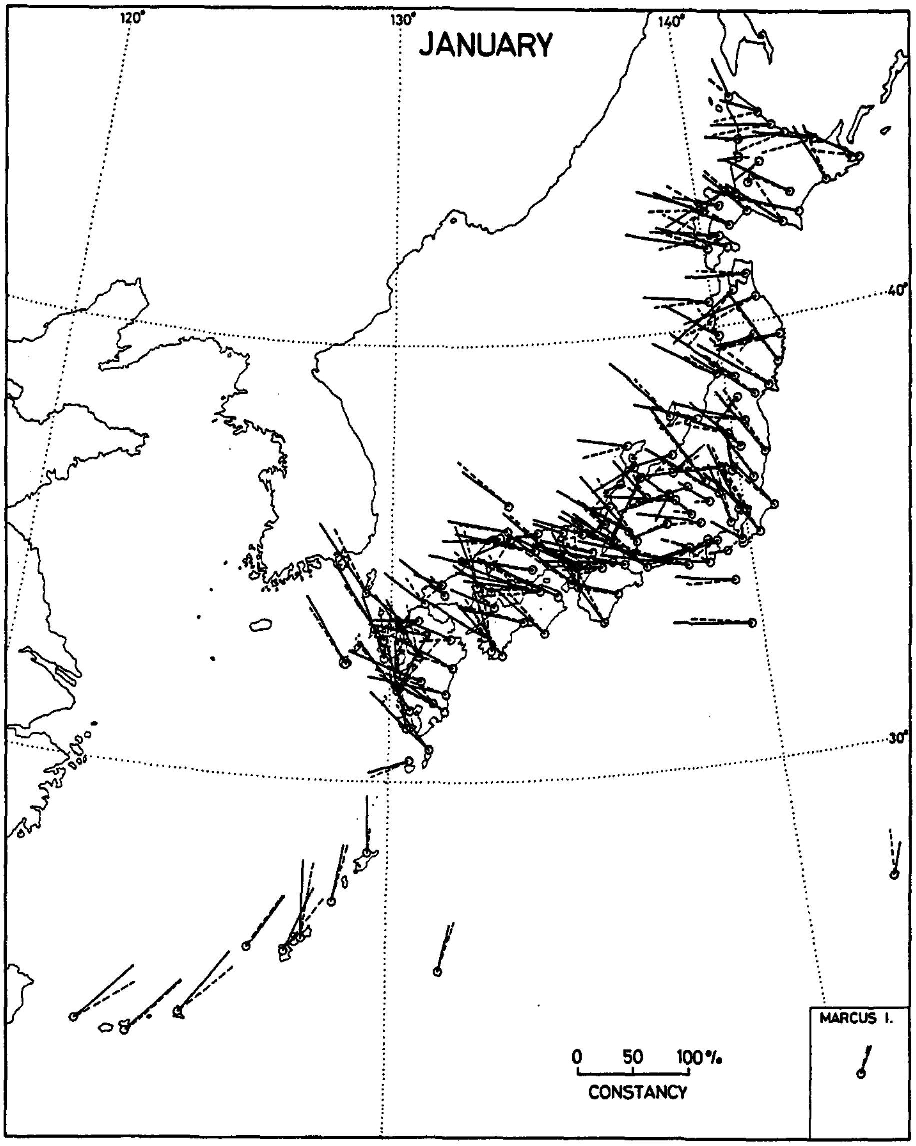

FIG. 7. Comparison between the direction of the mean vector wind and the mean of the wind direction in January. The solid lines show the direction of the mean vector wind and the dashed lines the mean of the wind direction. Lengths of the lines represent the constancies of wind direction according to each definition of *Cv* and *Cr*.

means, *Cv*, also represents a measure of the constancy of the wind (Davis, 1893):

$$Cv = \frac{Vv}{Va}. \qquad (6)$$

Thus, the constancy of the wind can be represented by the two measures of *Cr* and *Cv*. Yamartino (1984) has suggested that if the fluctuations in wind speed about the mean are uncorrelated with fluctuations in wind direction, *Cv* is equal to *R* (and *Cv* = *Cr*). However, this assumption cannot be expected to be satisfied especially in climatological wind data. Actual relationships between *Cv* and *Cr* have not been investigated.

2) RESULTS OF ANALYSIS

It has already been suggested that the mean of wind direction is generally a good approximation to the direction of the mean vector wind (Davis, 1893; Mintz and Dean, 1952). Mintz and Dean (1952) compared the directions of the vector mean wind and the mean of the wind direction at 67 stations in the United States and found that an appreciable discrepancy between the two directions occurs only where the magnitude of the vector mean wind is very small. However, detailed investigations have not been presented.

The same analysis has been made for the 152 stations in Japan. As an example, the result for January is shown in Fig. 7. On the whole, the angles between the two directions are very small. However, some sites show large discrepancy. It is evident that if the mean velocities estimated for each direction are all equal to each other, the direction of the resultant wind is equal to the mean of the wind direction. This is a necessary condition, but not a sufficient one. When there is a prevailing wind direction and the mean wind speed for this direction is relatively large, the resultant wind becomes large. Therefore, where the resultant winds are large, the angles may be small. On the other hand, if a prevailing wind direction does not exist or does not agree with a direction where the mean wind speed is relatively high, the angle between two wind directions may become large.

The relationships between the magnitude of the resultant wind and the angles between the two mean wind directions for January and July are shown in Fig. 8 for the 152 sites in Japan. The deflection angles are scattered widely where the resultant wind speeds are small and in some cases the absolute values of the angle exceed 90°. However, the values of the angles are less than about 30° where the resultant wind speeds are larger than 1.5 m s^{-1}. The angles scatter near 0° and have no tendency to incline toward one side. The large angles occur where the frequency distributions of the wind are as mentioned above.

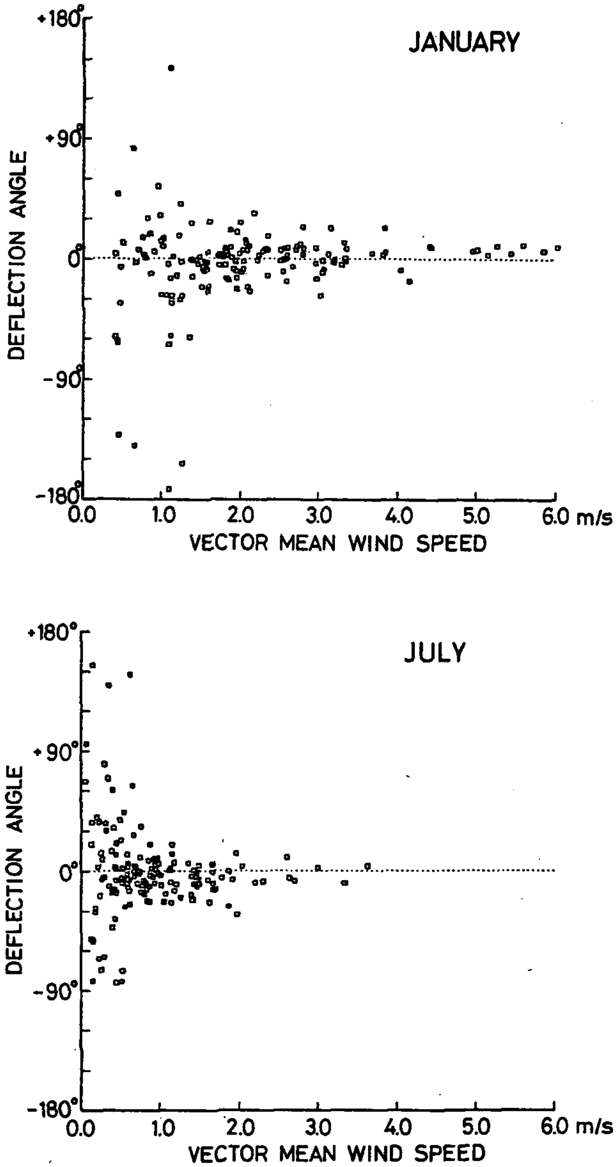

FIG. 8. The relationships between the deflection angle and the vector mean wind speed for January and July. The angles are positive when the means of wind direction rotate clockwise from the directions of the mean vector wind.

The distributions of *Cv* and *Cr* for January are also shown in Fig. 7. In this figure the magnitudes of *Cv* and *Cr* are represented by the lengths of the lines and these at each site do not necessarily agree. In order to clarify the relationship between *Cv* and *Cr*, the relationships in January and July are shown in Fig. 9. The magnitudes of the constancy of both definitions are generally smaller in July than in January. The relationships between *Cv* and *Cr* are rather scattered. There are rough relationships between *Cv* and *Cr*, and the magnitude of *Cr* tends to be smaller than that of *Cv*. This means that the fluctuations in wind speed are correlated with fluctuations in wind direction; the mean velocities estimated for each direction are not all equal

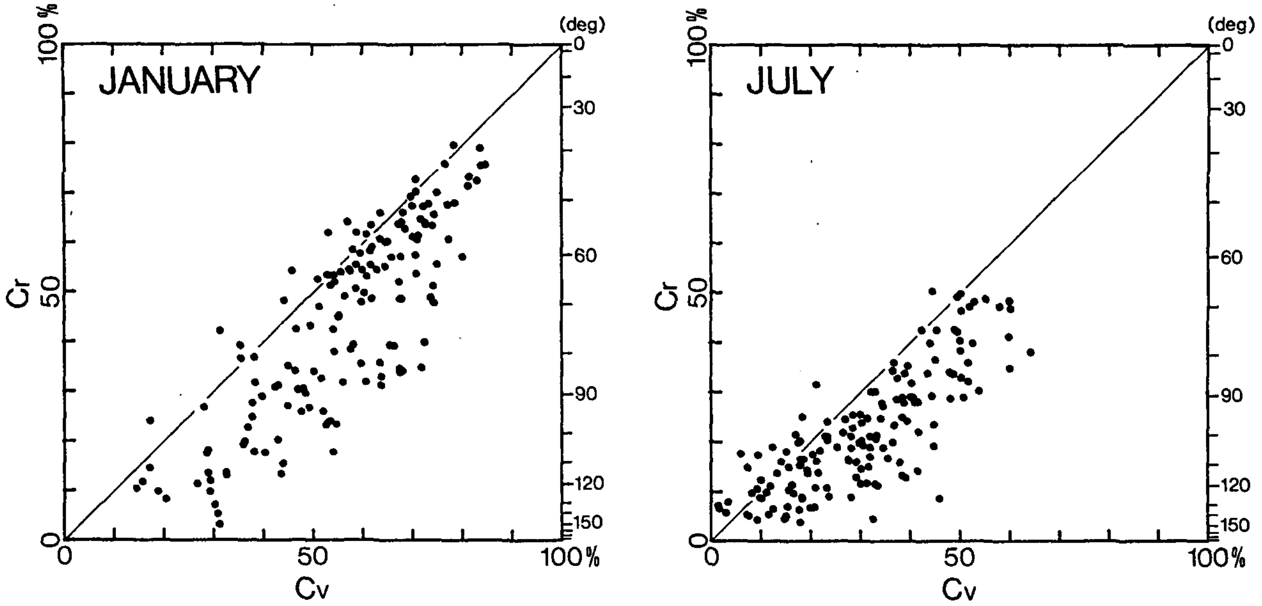

FIG. 9. The relationships between *Cv* and *Cr* for January and July. Scales on the right-hand side ordinates of each figure indicate the corresponding standard deviation of wind direction calculated from (4).

to each other and these tend to be larger in prevailing wind directions.

4. Conclusions

The vectorial treatment of the surface wind has revealed characteristics of climatological aspects of wind fields in Japan. The annual resultant surface winds are westerly at latitudes higher than 30°N and easterly at lower latitudes. The patterns of the annual variations of the wind in Japan will be presented in Mori (1987). change with latitude at about 30°N. The monthly resultant 850 mb winds have westerly components throughout the year at higher latitudes, but these components rotate once per year at lower latitudes. Physical interpretations for these climatological characteristics of the wind in Japan will be presented in Mori (1987).

The magnitude of the annual variation of the vector wind tends to increase with the increase of the annual mean scalar wind speed, while the relationships between the magnitude of the annual variation of scalar wind speed and the annual mean scalar wind speed are very scattered. Therefore, the sites where the annual mean wind speeds are high do not always show large annual variations of scalar wind speed.

The vector mean wind direction agrees with the mean of wind direction within 30° where the magnitude of the vector mean wind is larger than 1.5 m s^{-1}.

The constancy of wind direction is represented by the two measures of *Cv* and *Cr*. The relationships between *Cv* and *Cr* are rather scattered, and the magnitude of *Cr* tends to be smaller than that of *Cv*.

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. The computations were made at the Computer Center of Kagawa University. This study was supported in part by a grant from the Ministry of Education, Science and Culture of Japan.

REFERENCES

Coffin, H. L., 1875: The winds of the globe. *Smithsonian Contributions to Knowledge,* **278,** Washington DC, 637–656.

Davis, T. H., 1893: A comparison of prevailing and resultant winds. *Mon. Wea. Rev.,* **21,** 365–367.

Gray, W. M., and B. R. Mendenhall, 1973: A statistical analysis of factors influencing the wind veering in the planetary boundary layer. *Climatological Research, The Hermann Flohn 60th Anniversary Volume,* Meteorological Institute, University of Bonn, 167–194.

Hoxit, L. R., 1974: Planetary boundary layer winds in baroclinic conditions. *J. Atmos. Sci.,* **31,** 1003–1020.

Japan Meteorological Agency, 1971: Aerological data of Japan, 5-year period averages (1966–1970). Japan Meteorological Agency, Tokyo.

——, 1976: Aerological data of Japan, 5-year period averages (1971–1975). Japan Meteorological Agency, Tokyo.

Johnson, M. E., and J. D. Kalma, 1986: Study of the dependence of surface wind direction in the gradient wind. *Mon. Wea. Rev.,* **114,** 257–269.

Kawamura, T., 1977: Flow patterns and wind systems. *The Climate of Japan.* E. Fukui, Ed. Developments in Atmospheric Science, 8, Kodansha and Elsevier Scientific Publishing Co., 199–208.

MacKay, K. P., 1971: Steady state hodographs in a baroclinic boundary layer. *Bound.-Layer Meteor.,* **2,** 161–168.

Mardia, K. V., 1972: *Statistics of Directional Data.* Academic Press, 357 pp.

Mintz, Y., and G. Dean, 1952: The observed mean field of motion of the atmosphere. Geophysical Research Papers, No. 17, Air Force Cambridge Research Center, Cambridge, MA, 1–65.

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

——, 1981a: On vector mean winds at various sites in Japan. (in Japanese with English abstract) Mem. Fac. Educ., Kagawa University, II, **31**, 143–172.

——, 1981b: On vector mean winds in Japan. (in Japanese) *Tenki*, **28**, 419–426.

——, 1982: On climatological aspects of daily variation of surface wind in Japan. (in Japanese) *Tenki*, **29**, 223–230.

——, 1983a: On climatological aspects of daily variation of surface winds in the coast of Seto Inland Sea—monthly variation. (in Japanese) *Tenki*, **30**, 19–30.

——, 1983b: On the mean wind direction and the constancy of wind direction in Japan. (in Japanese) *Tenki*, **30**, 217–223.

——, 1983c: On the daily and annual variations of winds at Tottori, Okayama, Tadotsu, Takamatsu and Kochi. (in Japanese) *Tenki*, **30**, 244–257.

——, 1983d: On climatological aspects of daily variation of surface winds in Japan (II)—Seasonal variation. (in Japanese) *Tenki*, **30**, 503–508.

——, 1986a: On climatological aspects of annual variation of winds in Japan. (in Japanese) *Tenki*, **33**, 539–549.

——, 1986b: Evaluation of several "single-pass" estimators of the mean and the standard deviation of wind direction. *J. Climate Appl. Meteor.*, **25**, 1387–1397.

——, 1987: Methods for estimating the mean and the standard deviation of wind direction. *J. Climate Appl. Meteor.*, **26**, 1282–1284.

——, 1988: A study on climatic aspects of winds in Japan. Part II: Mean fields of the thermal wind. *J. Climate*, **1**, 143–156.

O'Brien, J. J., 1974: Rotary wind spectra in a sea breeze regime. *J. Appl. Meteor.*, **13**, 820–825.

Sheppard, P. A., H. Charnock and J. R. D. Francis, 1952: Observations of the westerlies over the sea. *Quart. J. Roy. Meteor. Soc.*, **78**, 563–582.

Yamartino, R. J., 1984: A comparison of several "single-pass" estimators of the standard deviation of wind direction. *J. Climate Appl. Meteor.*, **23**, 1362–1366.

Yoshino, M., 1966: Some climatological aspects of winds in Japan. (in Japanese with English abstract) *Chirigakuhyoron*, **39**, 20–30.