A Study on Climatological Aspects of Winds in Japan.
Part II: Mean Fields of the Thermal Wind

YUKIHIRO MORI

Earth Science Laboratory, Kagawa University, Takamatsu, Japan

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ABSTRACT

Climatological aspects of the geostrophic wind calculated from geopotential heights in the planetary boundary layer in Japan have been investigated. The mean geostrophic winds at the 850 mb level nearly agree with the observed 850 mb winds in both magnitude and direction, with some exceptions. The mean geostrophic wind vectors at the 850 mb and 1000 mb levels for each site are significantly different from each other, especially in winter. This suggests that the large thermal wind exists in the 1000–850 mb layer. It is suggested that the mean geostrophic wind shear is nearly constant with height in this layer.

1. Introduction

Climatological means for the surface and 850 mb winds in Japan have been investigated by Mori (1987; hereafter Mor87). It has been found that there is a large difference between the two means: at some sites, the mean surface and 850 mb winds are opposite to each other in direction at times. This cannot be explained by the effects of the surface drag and the Coriolis force only, but suggests that the thermal wind exerts strong influence on the wind profile in the planetary boundary layer (PBL).

Sheppard et al. (1952) have found that the vertical gradient of wind speed is of the same order at all levels in the westerlies and have suggested that the vector variation with height in the 200–500 m layer is due to the thermal wind. Gray and Mendenhall (1973) have statistically analyzed low-level radiosonde wind data over the sea and have found that the observed hodographs are strongly affected by the thermal wind. Hoxit (1974) has investigated the cross-isobar angles of the surface wind in baroclinic conditions by using low-level radiosonde data of wind and temperature.

Many studies of the modification of the Ekman spiral in baroclinic conditions have been made theoretically. In the modeling of the planetary boundary layer (PBL), the geostrophic wind shear is usually assumed to be constant with height (for example, Blackadar, 1965; Fortak, 1970; Schaefer, 1973; Gray and Mendenhall, 1973; Venkatesh and Csanady, 1974; and others). On the other hand, the utilization of a geostrophic wind vector which is an exponential function of height has been discussed by Mahrt and Schwerdtfeger (1970), and MacKay (1971). Mahrt and Schwerdtfeger (1970) discussed their results with reference to the flow in the PBL over the Antarctic Plateau. Which model of the geostrophic wind shear is preferable for the PBL at midlatitudes should be evaluated on the basis of observational data. However, the mean state of the thermal wind in the PBL has not been investigated.

In the present paper, first, the relationship between mean fields of winds and pressure in Japan is investigated. Second, climatological means of the thermal wind in the PBL are investigated from mean fields of pressure and temperature.

2. Data and analysis

Low-level radiosonde data at the aerological observatories in Japan were used in the present study. The locations of the sites are shown in Fig. 1 of Mor87. The Japan Meteorological Agency (JMA) has published statistical data of upper air observations from Japanese stations (JMA, 1983a,b). Monthly means of geopotential height, wind and temperature on the standard isobaric surface for each observation time, each month, and each station have been presented in these publications. From this dataset consideration was first given to changes due to expansion of station network and improvements in instruments and 20-yr means of the meteorological elements were obtained for the period from 1961 to 1980. This period is not the same as that of the 850 mb wind data analyzed in Mor87, but includes that period. The monthly means were originally

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

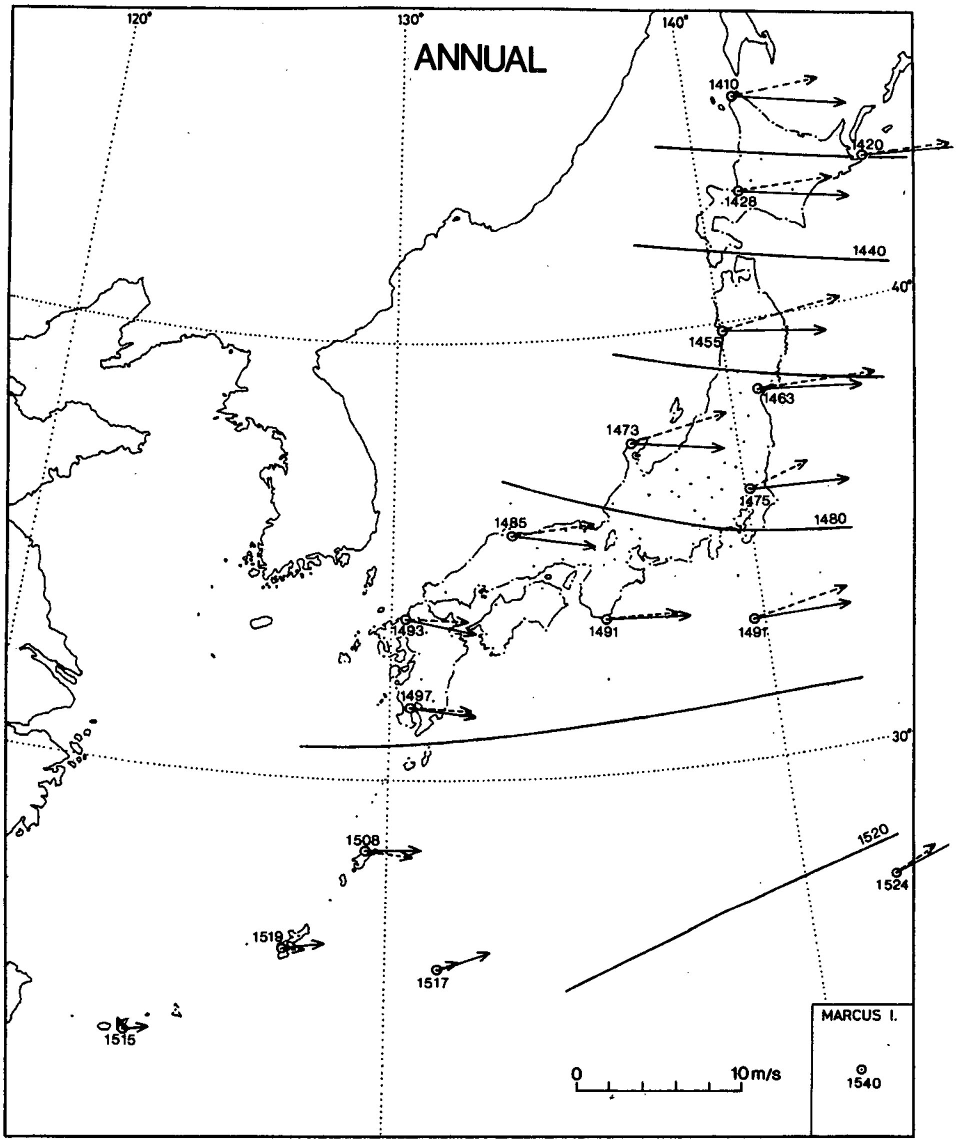

FIG. 1. Distributions of the geostrophic and the observed winds (annual). Numbers indicate mean geopotential heights in m. Dashed arrows indicate mean observed wind vectors and solid arrows indicate mean geostrophic wind vectors. Contours (solid lines) were drawn subjectively. (a) 850 mb; (b) 1000 mb. Note that the observed winds at 1000 mb are not available at Hachijō-jima, Kagoshima, and Naze.

given for each of the observation times of 0900 and 2100 JST (Japan Standard Time). The two means for each observation time for each month were averaged and the result is used as a mean for this month.

Mean geostrophic winds were not calculated from each day's pressure field, but from mean pressure fields. Applying the least-squares method, a second-order surface was fitted to the mean geopotential heights at 17 stations (except for Marcus Island) as follows:

$$H(x, y) = B_1x^2 + B_2y^2 + B_3xy + B_4x + B_5y + B_6 \quad (1)$$

where H is the geopotential height, and x and y the distances in the east–west and north–south directions, respectively. Once a second-order surface of geopotential height for some pressure level is fixed, the geostrophic winds at arbitrary points can be calculated from the derivatives of the second-order surface equation.

Means of the geopotential heights for the 1000, 900, and 850 mb levels were made for each site on a monthly and annual bases. In the case of the analysis of the 1000 mb level, observational data were not available

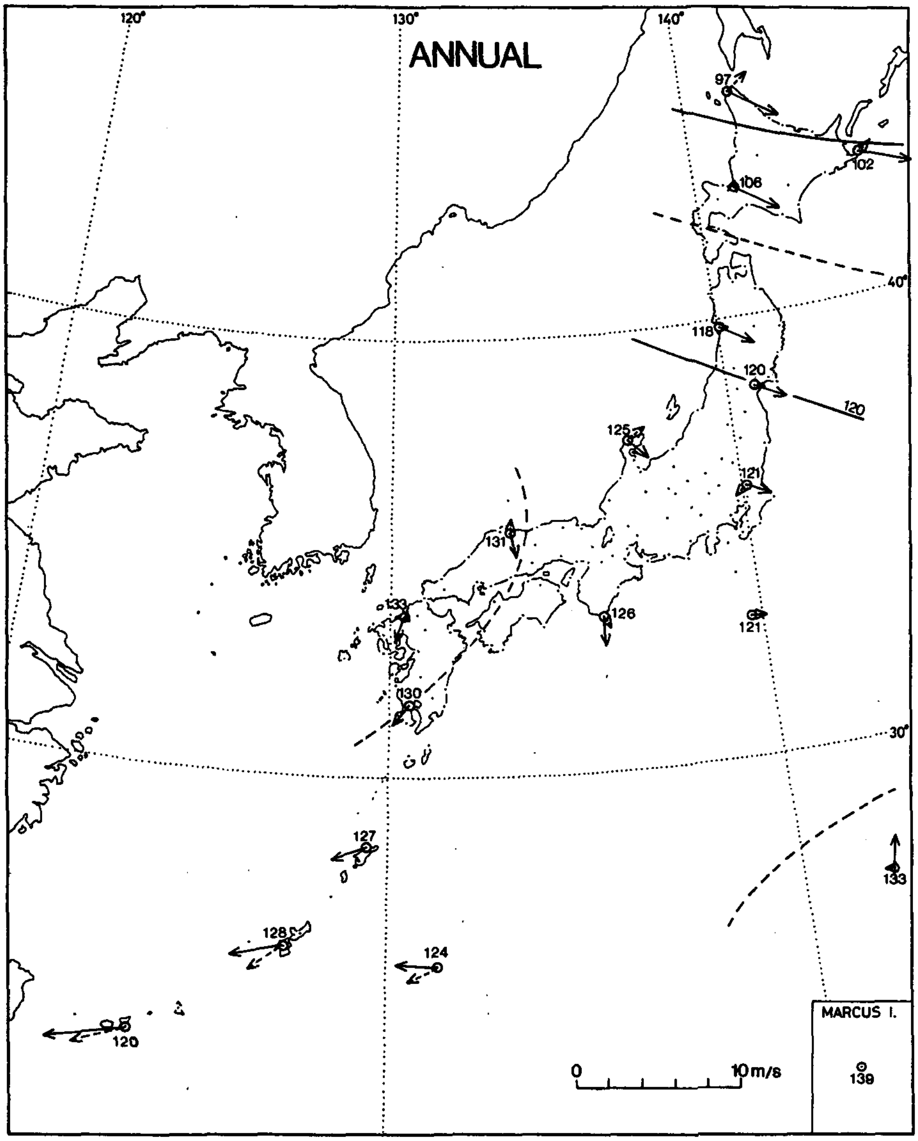

FIG. 1. (*Continued*)

at three stations of Hachijō-jima, Kagoshima, and Naze, because the station elevations of these sites are high.

3. Results

a. The mean observed and geostrophic winds at the 850 mb level

The annual mean observed 850 mb winds were compared with the calculated annual mean geostrophic winds for the 850 mb level in Fig. 1a. The geostrophic winds are westerlies in the whole area. The directions of the observed winds are rotated counterclockwise from the geostrophic winds at latitudes higher than about 30°. However, the angles are small, less than 30°. The magnitudes of the geostrophic winds almost agree with those of the observed winds in the main islands. On the Ryūkyū islands, the directions of both winds agree well, except for Ishigaki-jima. However, the magnitudes of the observed winds are less than half of those of the geostrophic winds at Naha and Minamidaitō-jima.

The annual mean observed and geostrophic winds for the 1000 mb level were also investigated. The relationship between both winds is shown in Fig. 1b. The direction of the geostrophic wind changes significantly

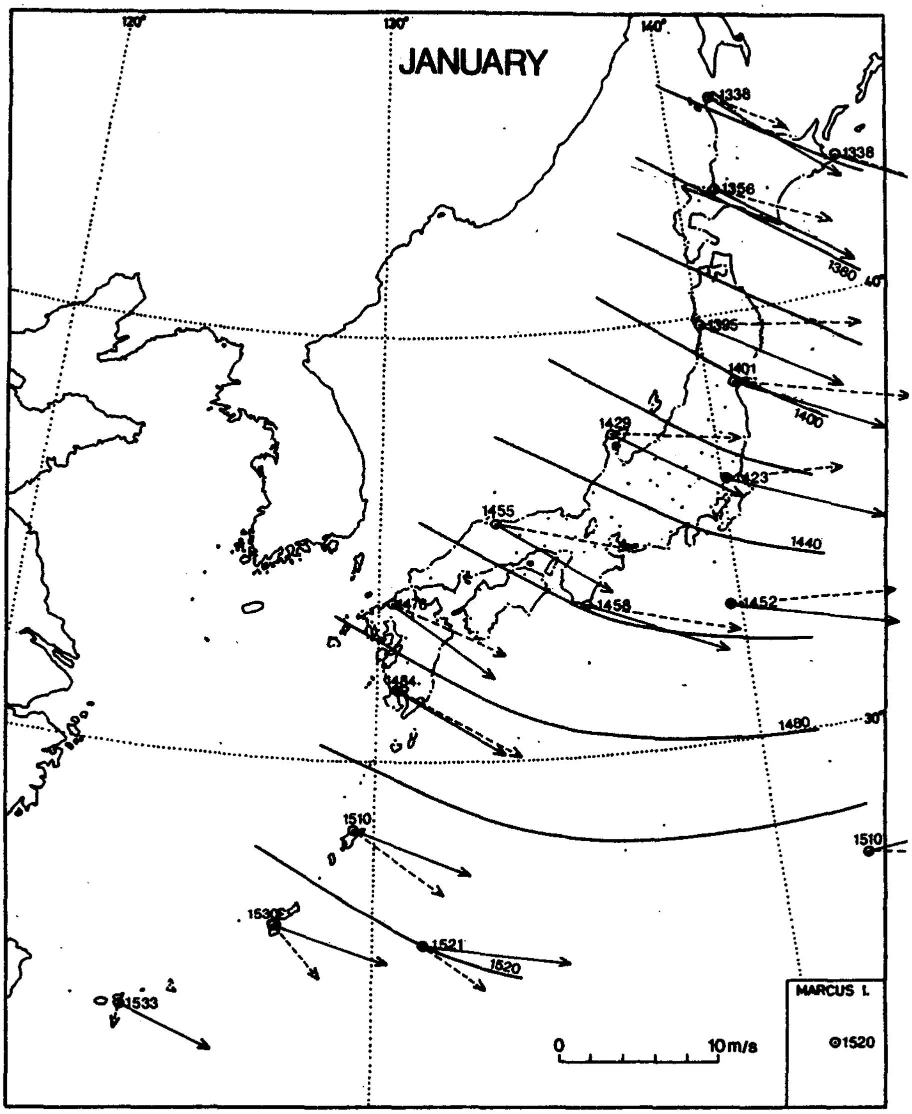

FIG. 2. As in Fig. 1, except for January.

with latitude; the geostrophic winds are northwesterlies at higher latitudes and easterlies at lower latitudes. The directions of the observed winds tend to be rotated counterclockwise from the geostrophic winds. The magnitudes of the observed winds are smaller than those of the geostrophic winds, as expected.

The relationships between the observed and geostrophic winds are investigated for the two extreme months of January and July. The relationship for the 850 mb level in January is shown in Fig. 2a. The directions of the geostrophic wind are NW or WNW. The directions of the observed wind tend to be rotated counterclockwise from the geostrophic winds at higher latitudes and clockwise at lower latitudes. The magnitudes of the observed wind almost agree with those of the geostrophic wind. Two exceptions are Naha and Minamidaitō-jima, where the magnitudes of the observed wind are nearly half of those of the geostrophic winds.

The relationship between the observed and geostrophic winds for the 1000 mb level in January is shown in Fig. 2b. The directions of the geostrophic wind are NNW at higher latitudes and NNE or NE at the Ryūkyū islands. The observed winds tend to be rotated counterclockwise from the geostrophic winds, but the angles are scattered.

The relationship between the observed and geostrophic winds for the 850 mb level in July is shown

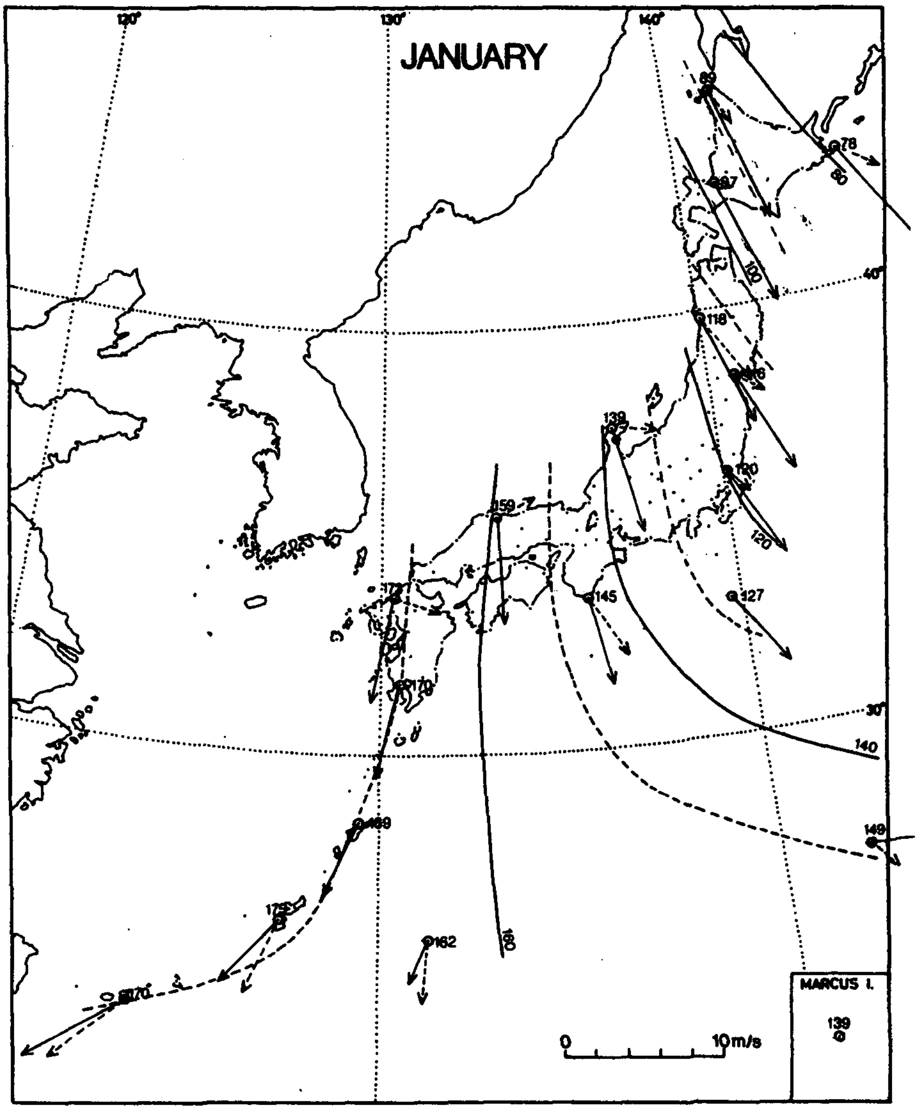

FIG. 2 (*Continued*)

in Fig. 3a. The directions of the geostrophic wind are SSW at lower latitudes and WSW at higher latitudes. The observed winds almost agree with the geostrophic winds except for Minamidaitō-jima and Chichi-jima. The relationship for the 1000 mb level in July is shown in Fig. 3b. The directions of the geostrophic wind are almost SSW in the whole area. The observed winds are rotated counterclockwise from the geostrophic winds except for Shionomisaki.

From the above comparisons between the observed and geostrophic winds and the comparisons for each month (not shown), it is concluded that the mean observed wind vectors at the 850 mb level nearly agree with the geostrophic winds calculated from the mean pressure field in both magnitude and direction. Therefore, the gross features of the annual change patterns of the 850 mb wind shown in Mor87 represent those of the 850 mb pressure field.

However, as mentioned previously, there are some discrepancies between the observed and calculated 850 mb winds. It is not clear whether these discrepancies are actual or not; the calculated geostrophic winds are derived from the smoothed surface fitted to the geopotential heights in an area as wide as the whole of Japan and there are some ambiguities in the estimation of the geostrophic wind.

The observed winds at the 1000 mb level are much smaller than the geostrophic wind in magnitude and tend to rotate counterclockwise from the geostrophic winds. This can be expected from the effect of the sur-

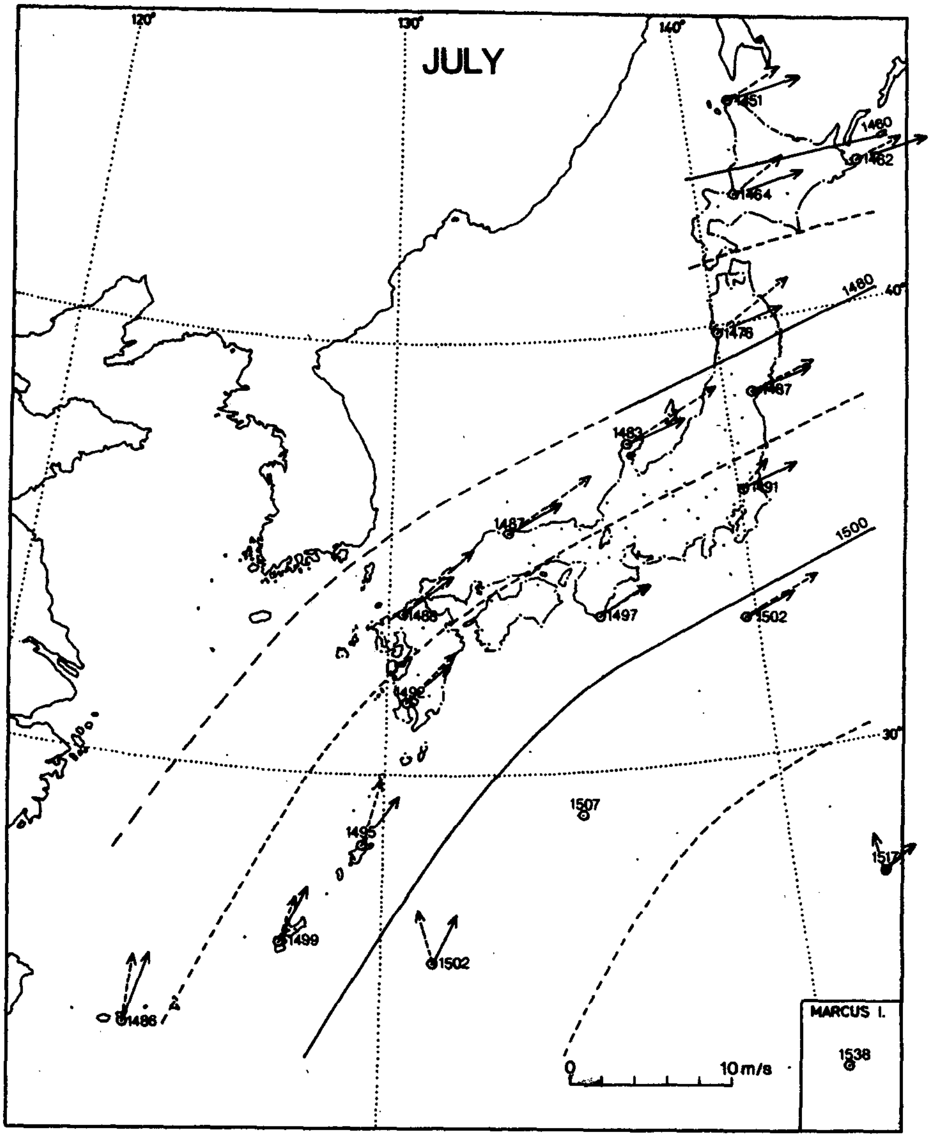

FIG. 3. As in Fig. 1, except for July.

face drag and the Coriolis force. The angles, however, are very scattered in the main islands; it is concluded that topography and local thermal effects significantly affect the wind observations at this level in the main islands.

Comparing the geostrophic winds at the 850 and 1000 mb levels for each site in Figs. 1, 2 and 3, it is found that the two wind vectors for each site are significantly different from each other in both magnitude and direction, especially in winter. This suggests that a large thermal wind exists in the layer between the 850 mb and 1000 mb levels which includes most of the PBL.

b. The thermal wind in the 1000–850 mb layer

The thermal wind is denoted by a geostrophic wind shear vector between two isobaric surfaces. On the other hand, when the temperature field between the two surfaces is known, the thermal wind vector can be calculated from the thermal wind equation. Then, thermal winds can be calculated from the two approaches.

The thermal wind calculated from the geostrophic winds at the 850 and 1000 mb levels is denoted here as V_T. When the mean horizontal temperature gradient on the 900 mb pressure surface is considered representative for the 1000–850 mb layer, the thermal wind

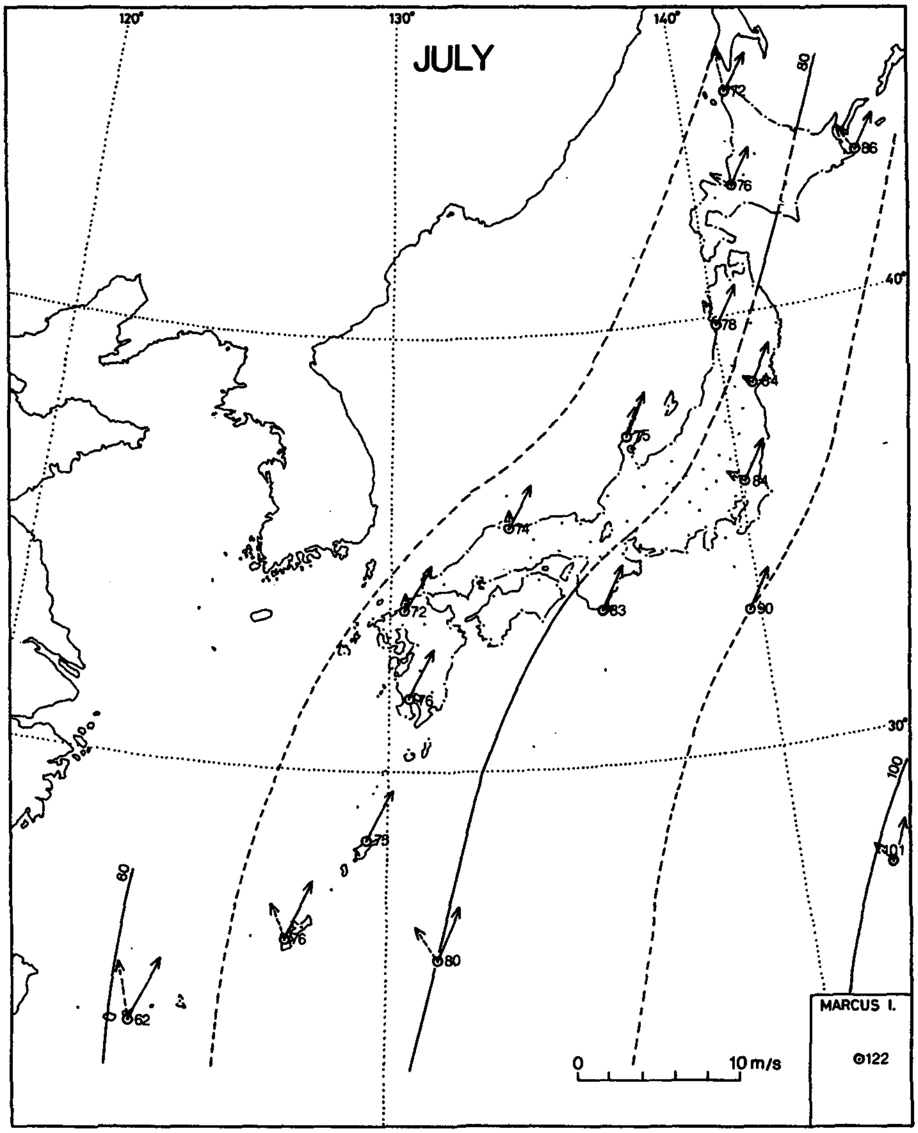

FIG. 3. (*Continued*)

can be calculated from the temperature field and is denoted here as V_{T900}. In the estimation of the thermal wind, the horizontal temperature gradient is obtained from the mean 900 mb temperatures for the 17 aerological observatories by using the same method as was used in obtaining the geostrophic wind in section 2.

The mean thermal winds V_T and V_{T900} for the annual, January, and July distributions are shown in Fig. 4a, b, c. In the annual distribution (Fig. 4a), it is found that V_T agrees quite well with V_{T900} at each site. The directions of the thermal winds are W or WNW. The magnitudes of the thermal wind decrease toward higher latitudes. However, the corresponding horizontal temperature gradients show only a small change in the range of 0.7–0.8×10^{-5} K m^{-1} (0.7–0.8 K/100 km).

In January (Fig. 4b), the magnitudes of the thermal wind are about 5 m s^{-1} at higher latitudes and about 10 m s^{-1} at lower latitudes. Thus, the thermal winds at lower latitudes are twice as large as those at higher latitudes. However, the horizontal temperature gradient corresponding to these thermal winds does not show a large latitudinal change; the magnitudes of horizontal temperature gradients are 1.2×10^{-5} K m^{-1} (1.2 K/100 km) at lower latitude and 1.4×10^{-5} K m^{-1} (1.4 K/100 km) at higher latitudes. The magnitude of the

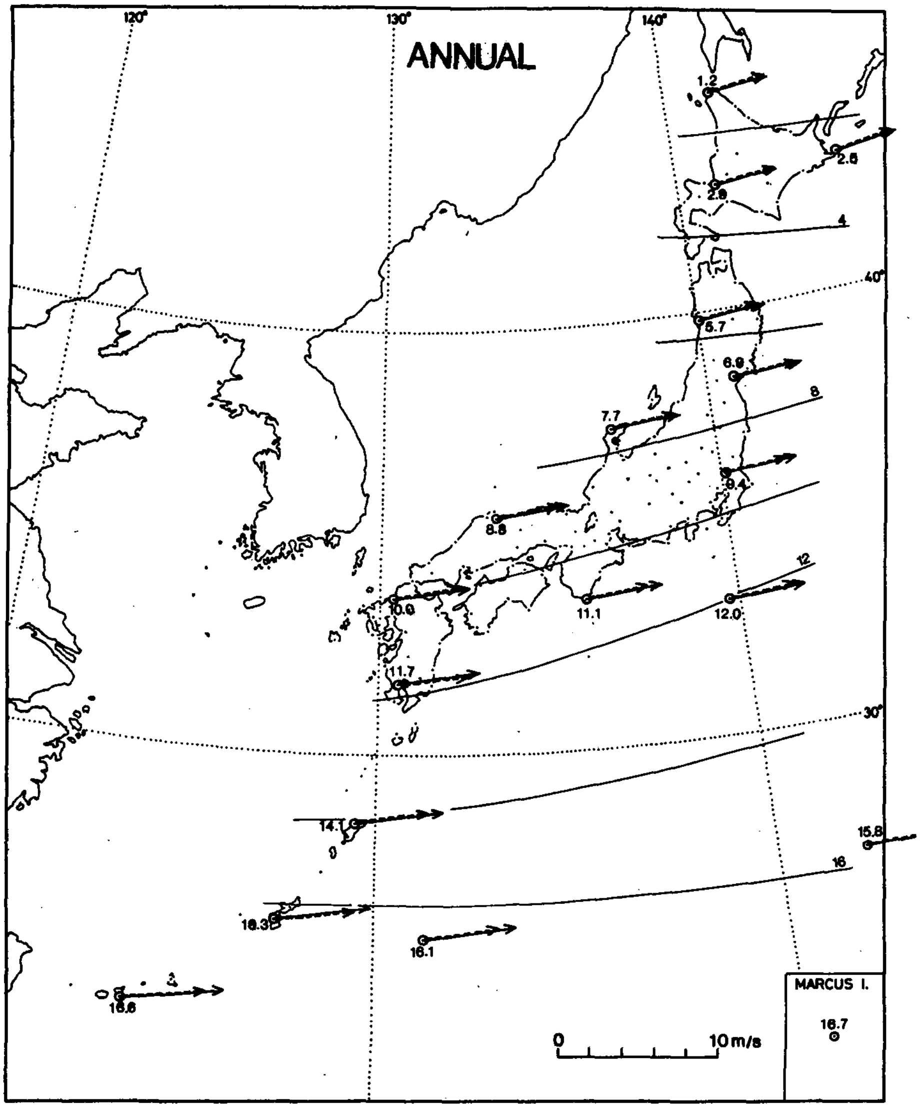

FIG. 4. (a) Annual; (b) January; and (c) July distribution of the thermal winds in the 1000–850 mb layer. Numbers denote values of mean temperature at the 900 mb level. Isothermal lines (solid) on the 900 mb surface were drawn subjectively.

thermal wind varies inversely with the Coriolis parameter which increases with latitude.

In July (Fig. 4c), the magnitudes of the thermal wind are generally smaller than those in January in the whole area. The directions of the thermal winds are WNW at higher latitudes. On the Ryūkyū islands, the magnitudes of the thermal wind are very small. The magnitude of the thermal wind at higher latitudes is about 2 m s^{-1} and the corresponding horizontal temperature gradients are 0.5×10^{-5} K m^{-1} (0.5 K/100 km).

The thermal winds in the 1000–850 mb layer were also calculated from mean horizontal temperature gradients on the 850 and 1000 mb pressure surfaces and are denoted here as V_{T850} and V_{T1000}, respectively. Monthly values of V_T, V_{T850}, V_{T900}, and V_{T1000} at Sapporo, Shionomisaki, and Naha are shown in Fig. 5. The magnitudes of V_T at each site show a large annual change; these are large in winter and small in summer; V_{T850}, V_{T900}, and V_{T1000} agree well with V_T in each month, except for V_{T1000} at Sapporo. This may suggest that the mean geostrophic wind shear in the PBL is constant with height.

In order to confirm this, mean geostrophic wind shears (GWS) are calculated for two layers of the 1000–

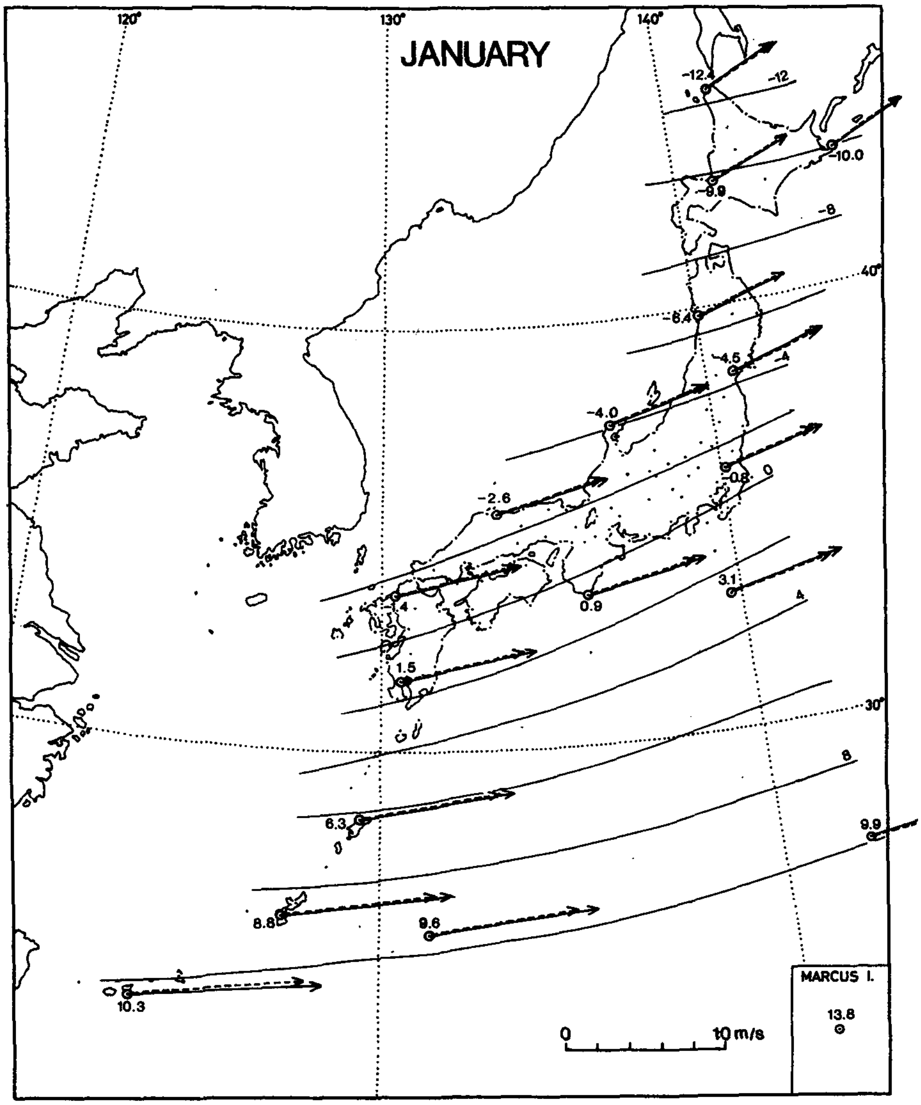

FIG. 4 (*Continued*)

900 mb layer and the 900–850 mb layer, and are denoted here as GWS1 and GWS2, respectively. The annual distributions of GWS1 and GWS2 are shown in Fig. 6. It is demonstrated that the two vectors of GWS1 and GWS2 at each site agree quite well. When we have analyzed GWS for each month (not shown), it has been found that agreement of both vectors at each site is good in the cold season but not so good in the warm season. However, in the warm season the magnitude of both vectors is small in the whole area. Then it can be concluded that GWS1 and GWS2 in the whole area agree well except for summer when the magnitudes of the thermal wind are small. Considering that the mean lapse rate of temperature in the PBL is constant with height, the above result suggests that the climatological mean geostrophic wind shear in the 1000–850 mb layer is constant with height.

MacKay (1971) has suggested that use of a geostrophic wind vector which varies linearly with height in numerical models, causes a discontinuity in both the geostrophic wind vector and the resulting horizontal wind vector at the top of the boundary layer. He subsequently discussed the utilization of a geostrophic wind vector which is an exponential function of height. However, the present result suggests that MacKay's model is not applicable in the modeling of the PBL in Japan.

If the geostrophic wind shear and the eddy viscosity

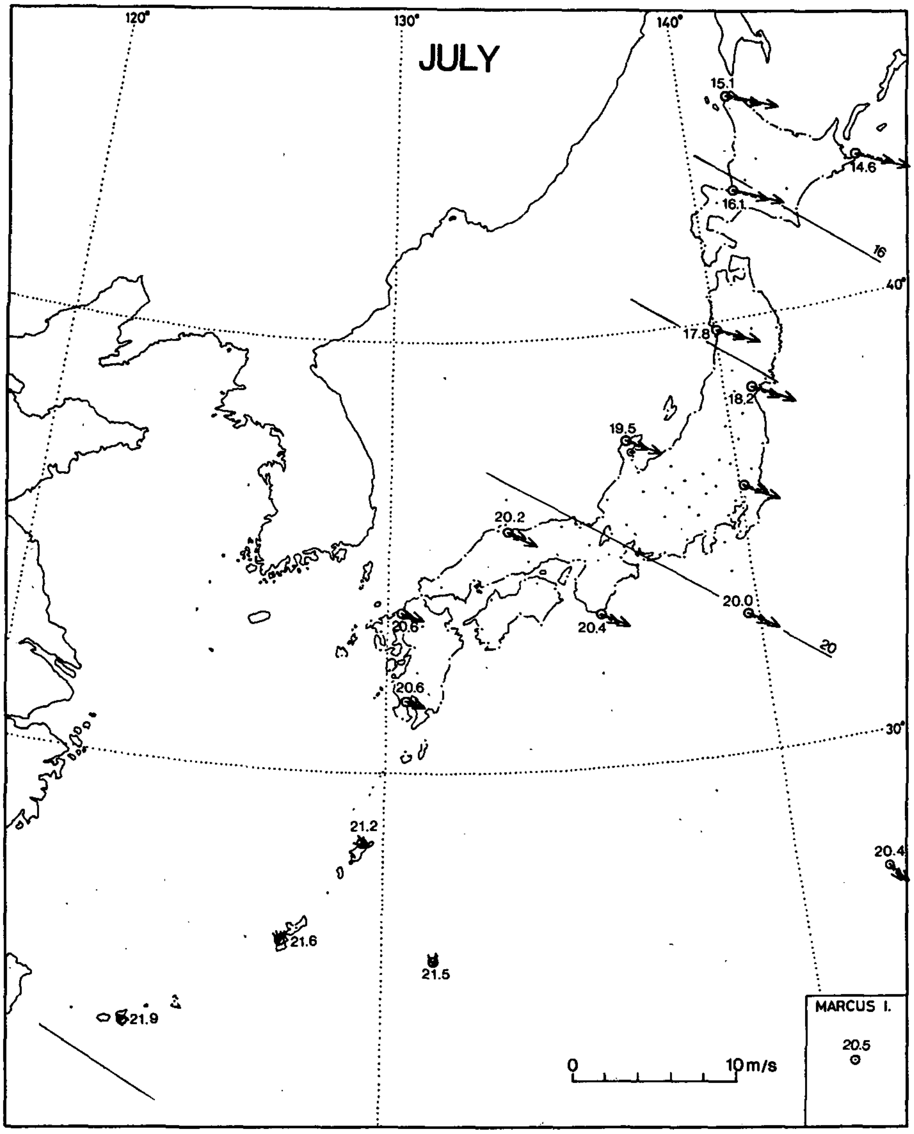

FIG. 4 (*Continued*)

in the PBL are constant with height, we can calculate winds in the PBL by using the Ekman-type model (Gray and Mendenhall, 1973). We intend to estimate the mean surface wind from the observed mean 850 mb wind by using the geostrophic wind shear calculated from the observed mean temperature field at the 900 mb surface. It is difficult to determine the value of K for the climatological condition, since it may vary with season and latitude. In this diagnostic calculation of the effect of the thermal wind in the PBL, we assume that $K = 1.0\ \mathrm{m^2\ s^{-1}}$ is constant with season and latitude. Considering that the nonslip condition is given at the surface, the wind at a height of 50 m, though the elevation is high, is calculated as the surface wind. By way of example, calculations are made for Wakkanai, Shionomisaki, and Naha. At these sites mean daily wind variations are relatively small.

Estimated monthly mean surface winds, V_{ST}, are shown in Fig. 7. For comparison, estimated winds without considering the thermal wind, V_S, are also shown. Annual change patterns for V_{ST} are quite different from those for V_S. The annual change patterns for V_{ST} at each site resemble those for the observed monthly mean winds more than the annual change patterns for V_S. The values of V_{ST} at each month do not necessarily well represent the corresponding ob-

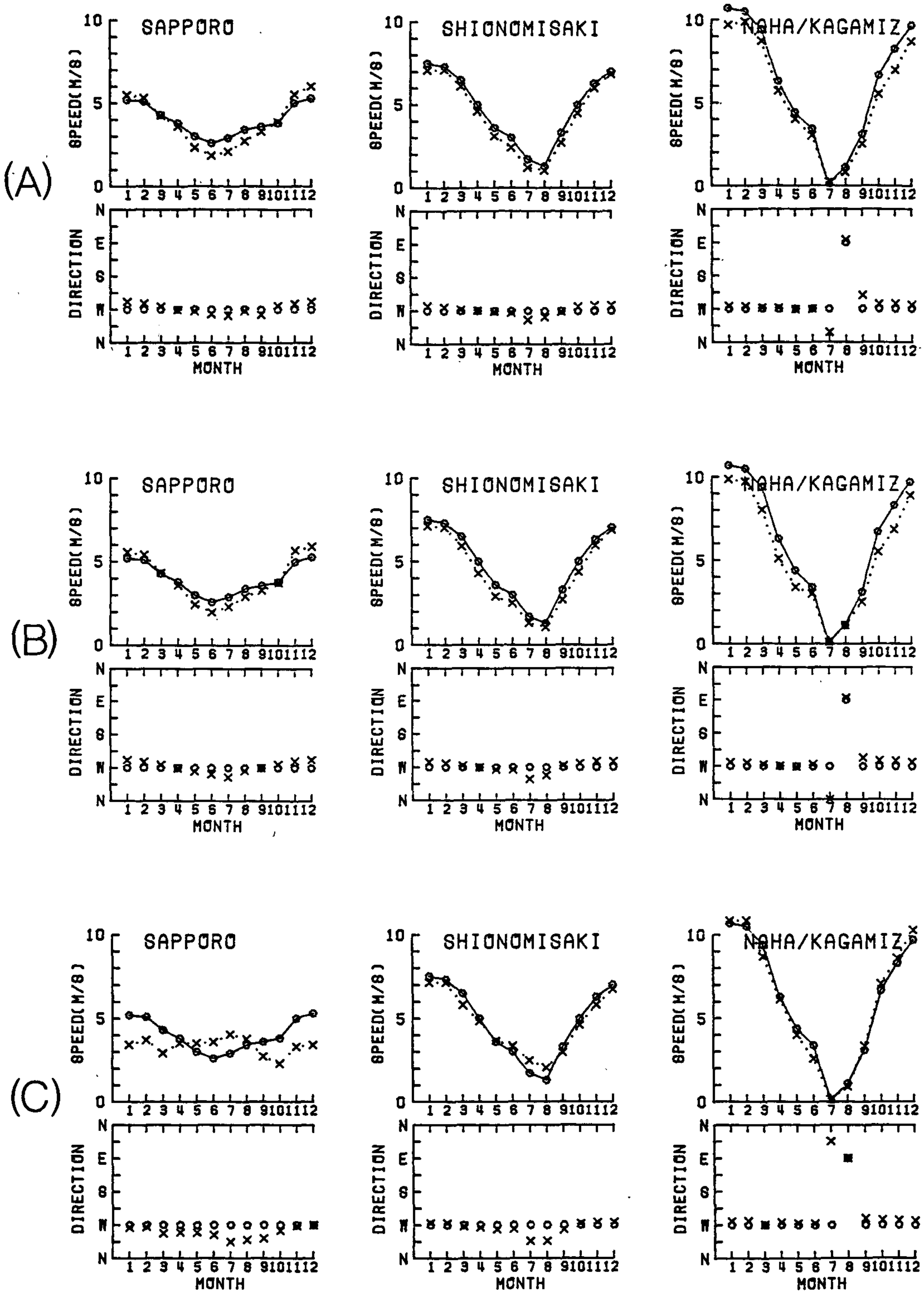

FIG. 5. Monthly means of the thermal wind in the 1000–850 mb layer at Sapporo, Shionomisaki, and Naha. Open circles indicate V_T and crosses indicate others. (a) V_T and V_{T850}; (b) V_T and V_{T900}; and (c) V_T and V_{T1000}.

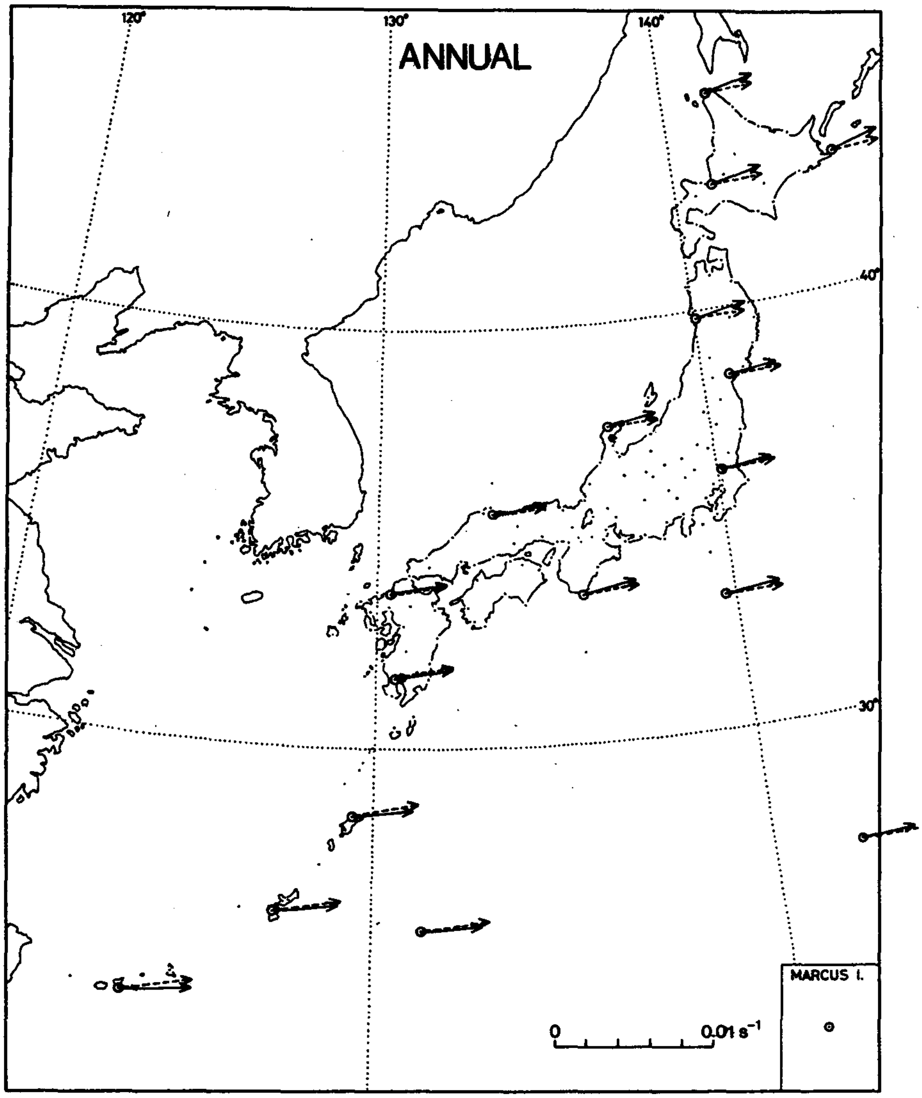

FIG. 6. The vectors of GWS1 and GWS2 for the annual distribution. Dashed arrows indicate GWS1 and solid arrows indicate GWS2.

served winds. Needless to say, the observed surface winds at each site are affected by topography and local thermal effects, so the discrepancies between the estimated and observed surface winds are due to not only the simplicity of the atmospheric model used but also to these local effects. However, despite these deficiencies, it is clear that the gross shapes of the annual change patterns for V_{ST} well represent the characteristics of those for the observed winds.

As shown in Mor87, at higher latitudes, the shapes described by the tips of the observed monthly mean surface wind vectors are similar to those for the corresponding 850 mb winds, but the westerly components of the monthly mean surface wind vectors are generally small; at lower latitudes, the shapes described by the tips of the monthly mean surface wind vectors are linear in the south–north direction and are quite different from those for the 850 mb winds, which are circular. These characteristics of the climatological mean winds in Japan can be explained by the effect of the thermal wind in addition to the effects of the surface drag and the Coriolis force.

4. Conclusions

Climatological aspects of the geostrophic wind in the PBL in Japan have been investigated. The mean observed 850 mb winds nearly agree with the calculated geostrophic winds at this level, so the gross features of

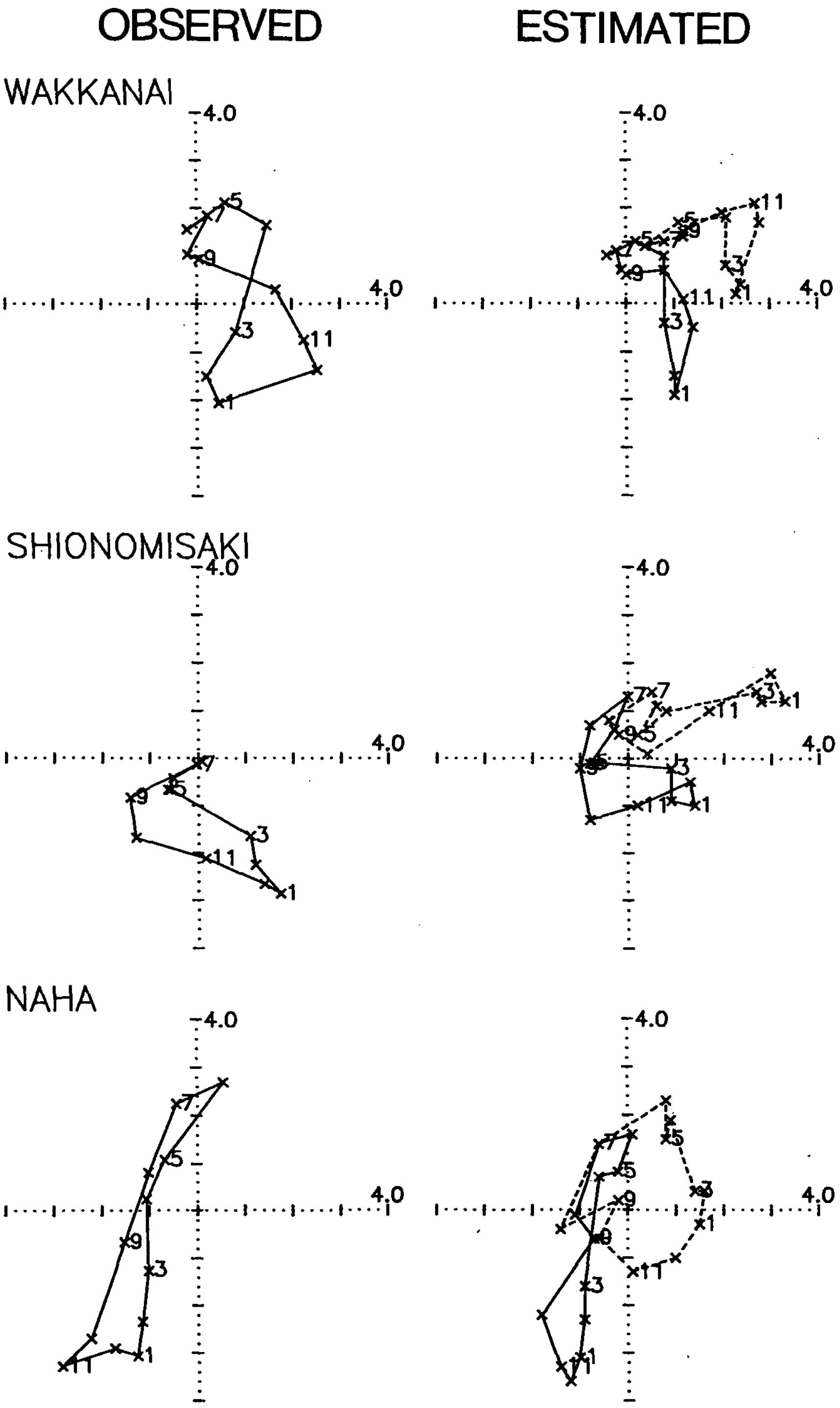

FIG. 7. The observed and estimated monthly mean surface winds for Wakkanai, Shionomisaki, and Naha. Solid lines on the right-hand side indicate the estimated winds which included the thermal wind effect, and dashed lines indicate the estimated winds which do not include thermal wind effect. Crosses denote the ends of the vectors for each month.

the annual change patterns of the 850 mb wind represent those of the 850 mb pressure field. The mean observed 1000 mb winds are much smaller than the calculated geostrophic winds at this level in magnitude and tend to rotate counterclockwise from the geostrophic winds.

It is found that the large thermal winds exist in the 1000–850 mb layer and the thermal winds in the area are almost westerlies throughout the year, and are large in magnitude in winter. It is suggested that the climatological mean geostrophic wind shear in the PBL is constant with height.

The characteristics of the difference between the annual change patterns of the surface wind and those of the 850 mb wind can be explained by the effect of the thermal wind in addition to the effects of the surface drag and the Coriolis force.

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