CLIMATIC CAUSES OF WIND-SHAPED FIR TREES AROUND THE SUMMIT OF MT. KINPUSAN IN THE CHICHIBU MOUNTAINS, CENTRAL JAPAN

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Abstract The purpose of this study is to examine the climatic causes of wind-shaped fir trees (their shape corresponds to Yoshino's type 2) in the subalpine zone belonging to the region of Pacific side climate with no precipitation from winter monsoons. For this, the area around the summit of Mt. Kinpusan, Central Japan, was selected. Twenty surface wind distribution examples in winter and summer were analyzed in relation to the winds aloft from a synoptic climatological point of view. As a result, wind-shaped trees there are considered to be formed essentially by the drier colder prevailing winter winds closely connected with desiccation damage. The winds with precipitation or icings in winter play only the secondary role in the formation of wind-shaped trees.

Key words: wind-shaped fir trees, surface wind distribution, synoptic climatological approach, desiccation damage, Mt. Kinpusan in the Chichibu Mountains

1. Introduction

It is important not only for climatology but also for every field of study including that of vegetation and of landforms to clarify the surface wind distribution on mountain area in micro- and meso-scale. The wind-shaped trees are believed to be an indirect but effective means for detecting the wind distribution in mountainous regions where meteorological stations are extremely sparse. In using the wind-shaped trees as an indicator of winds in these areas, important points are to know how these trees have been deformed by winds and what kind of winds wind-shaped trees actually indicate.

As an initial step to approach this problem, I have examined the climatic causes of the wind-shaped trees (*Abies mariesii*) on the southern ridge of Ozegahara, which belongs to the region of Japan Sea side climate characterized by snow fall in winter monsoons (Ogawa, 1974). The result indicates that the colder drier and stronger winds in winter play the most important role in forming the wind-shaped trees in the area, and that the prevailing winter winds accompanied by heavy snow act as a preventing factor for their

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formation. Moreover, on the basis of these results, I suggested in the previous paper that the formation of the wind-shaped trees in subalpine zone of the mountains belonging to the region of Pacific side climate was also inferred to be connected with the drier colder winter winds, namely prevailing winter winds in this area. This inference, however, differs from the opinion that the prevailing winds during warm season are the formative factor in this climatic region (Yoshino, 1973; Kai, 1976).

In the present study, in order to examine this "drier colder prevailing winter wind" hypothesis, I selected an area around the summit of Mt. Kinpusan (2,599 m a.s.l.) in the Chichibu Mountains, which belong to the region of Pacific side climate. And taking a

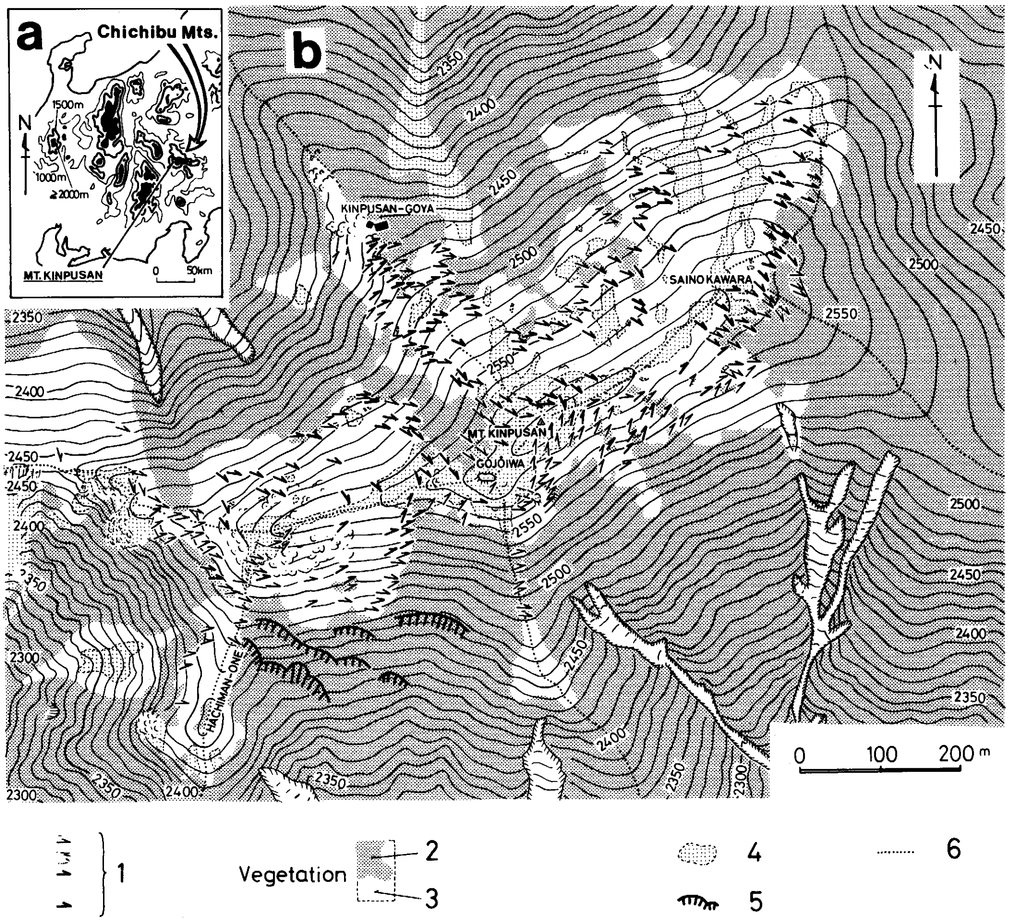

Fig. 1 a: Location of study area
b: The distribution of wind-shaped trees (*Abies veitchii* and *Abies mariesii*), the vegetation, and the *Shimagare* phenomenon around the summit of Mt. Kinpusan

1: wind-shaped trees. Arrow shows grade of deformation and the wind direction estimated from it; 2: subalpine conifer forest; 3: *Pinus pumila* scrub; 4: blocks; 5: *Shimagare* phenomenon; 6: divide.

synoptic climatological approach, the same as in the previous examination above, I studied the climatic causes of wind-shaped trees. The result of this study was in support of this hypothesis.

In this paper, I will report the result in detail, and in addition, briefly describe the *Shimagare* phenomenon in this area in relation to the problem of wind-shaped trees.

2. Distribution of Wind-shaped Trees around the Summit of Mt. Kinpusan

Study area

The main range of the Chichibu Mountains, rising to heights of 1,600-2,600 meters, extends from east to west in the middle of the Kanto Mountains. The study area, Mt. Kinpusan is located near the western end of the range, and forms one of the highest summits there (Fig. 1-a).

The Chichibu Mountains are considered to belong to the region of Pacific side climate (the climatic region of Front-Japan type) characterized by no precipitation from winter monsoons (Suzuki, 1962). This has been confirmed by using the weather records in the manager's diary (the details of the weather records will be described later) at the Kinpusan-*goya* (a hut—2,450 m a.s.l.—located on the north slope about 300 m north of the summit). According to these records, out of the selected 57 days in 1970-1980 with typical winter pressure pattern, 46 days were clear or fine, seven days were cloudy or foggy, and only three days were with precipitation.

Main ridge around the summit of Mt. Kinpusan runs also from east to west. Strictly speaking, it extends from ENE to WSW and then turned to WNW at a junction peak from which the Hachiman-*o'ne* (the branch ridge) extends southward (Fig. 1-b). On both sides of the main ridge, there spread smooth block slopes formed under the periglacial condition during the Last Glacial Age (Shimizu, 1983), and the most parts of the slopes are now covered with *Pinus pumila* scrub.

The wind-shaped fir trees are generally found all over the *Pinus pumila* scrub range of the above slopes in patches or in isolation. And the deformation of trees there is the most developed one both in number and in grade among the Chichibu Mountains, according to my general survey along the main ridge of the mountains. This predominance of wind-shaped trees is one of the main reasons why the area in the above was selected as a study area among many mountains belonging to the region of Pacific side climate. Another main reason for the selection is that, in this area with the main ridge extending from east to west, it is easier to distinguish the prevailing winds in winter and in summer than in an area with the main ridge running from north to south.

Pinus pumila scrub, interspersed with the wind-shaped fir trees, passes into the lower subalpine conifer forest at altitudes of about 2,450-2,500 meters. In the forest, *Shimagare* phenomenon ("wave-regeneration" characterized by some crescent-shaped stripes of conifer trees standing dead) is observed on the S-facing slopes as it is in other portions of the Chichibu Mountains. Above all, the one found just to the east side of the Hachiman-*o'ne* on the south slope of the main ridge has very clear stripes and its arrangement.

Distribution of the wind-shaped trees

As mentioned above, most of the wind-shaped fir trees are distributed among the *Pinus pumila* scrub, but in part, they are also found at the margin of the subalpine forest. On the north side of the main ridge, they are widely distributed at elevations over about 2,500 meters, partly down to 2,450 meters along the minor ridge. Whereas, on the south side, they are limited to a narrow area extending only to 2,550 meters just below the main ridge, except the both sides of Hachiman-*o'ne*.

The majority of the wind-shaped trees there are of *Abies veitchii* and, partly of *Abies mariesii*. As to their shape of deformation, the branches on windward side are mechanically injured and severed in the same manner as in the southern ridge of Ozegahara (Fig. 2). This seems to correspond to the Yoshino's type 2 (Yoshino, 1973). The type of deformation is found on any slopes and at any altitudes in the range of the wind-shaped trees of this area.

The field intensive observations of these wind-shaped trees were carried out from 1974 to 1979 with the following method. The direction of deformation was measured by a compass attached to a clinometer, by which the surface wind direction was estimated. As to the grade of deformation, the lengths of Parts a, b, c and c' in Fig. 2 were measured; then according to the value of c/c', the grades were classified into three groups. That is, the values of 3.0 and 6.0 were taken as threshold ones for convenience. This scale was introduced here, because it seemed to have comparatively good correlation to the surface wind speed distribution to be described later. In this connection, Yoshino (1973) classified the grade of type 2 into five classes according to the length of the remnants of the twigs and branches from the tree-top on windward side of trunks. However, in the deformation in higher grade in my scale in this area, the twigs and branches just below the tree-top usually still remain, his scale therefore was not adopted here.

The results are plotted on the map as shown in Fig. 1-b. Each arrow in this figure indicates the grade of deformation and the wind direction estimated from one wind-shaped tree at the point, but partly indicates the average grade and direction from a few trees around the point. In this figure, we find the following as to the wind

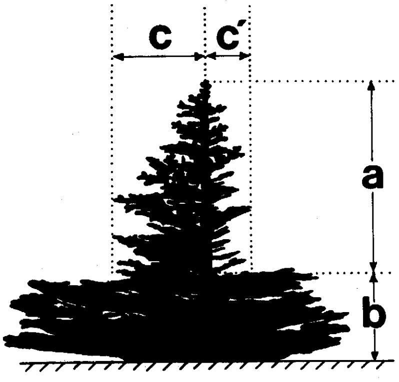

Fig. 2 A typical example of the wind-shaped trees found in the study area
The lengths of Parts a; b; c; c' were measured, and the value of c/c' was adopted as the scale of deformation grade.

distribution estimated from the wind-shaped trees.

1) Generally, the westerly winds, facing the mountain body of Mt. Kinpusan, ascend the slope of the mountain in a curved way, that is, on the north slope they turn into the northwesterly winds. On the south slope the westerly winds become southwesterly winds in the same way. Thus, they "converge" near the divide line of main ridge.

2) Ascending winds on the north slope are "strong (the grades are in greater part medium or higher)." Moreover, at Saino-kawara and south of Gojoiwa, they blow over the divide line and reach the south slope. Consequently, around these parts northerly winds and southerly winds seem to "alternate."

3) On the south slope, winds are generally "weak." This tendency also is seen on the west of Hachiman-*o'ne* exposed to the westerly winds.

Then, of which season and of what nature does this "wind" distribution pattern indicate?

From 1) above, we can assume that this is not the distribution pattern of thermally induced winds as a valley breeze but that of mechanically induced winds. Moreover, from these differences both in the deformation grade and in its distribution range on the north slope and the south slope, we can infer that the distribution pattern shows that of winds in winter and not that of in summer.

3. Method of Analysis

In order to examine what kind of winds, including this inference above, the deformation indicates, in other words, to examine the wind factor determining the deformation, a synoptic climatological approach was introduced again, as previously stated. The practical procedures are as follows:

1) The first stage is to detect surface wind distributions in the study area, so in detail as to be compared with the distribution of the wind-shaped trees. Then it is necessary to classify the patterns of the wind distribution obtained.

2) The second stage is to determine which synoptic wind condition and air flow pattern aloft each type of patterns of the surface wind distribution classified above is associated with.

3) The third stage is to calculate the occurrence frequency of each air flow pattern for several years, in consideration not only of seasons and wind speed but also of occurrence or nonoccurrence of precipitation and the temperature of each air flow pattern.

On the basis of these analyses, the climatic causes of the wind-shaped trees in this area will be discussed.

4. Surface Wind Distributions and Their Synoptic Climatological Analysis

Surface wind observation

In 1975-1978, we visited the study area six times both in winter and summer to carry out the moving observations of surface wind under the various synoptic wind conditions. The observations from one day to four days were done within one visit to the area, using the Nakaasa-type portable anemometer and anemoscopes. One set of measurements took mostly one hour to two hours and a half, and usually two sets of measurements were made in a day. These measurements clustered around 0900 JST in one set and 1500 JST in the other (two observation times of upper air data in aerological stations out of four). When measurements were made, for unavoidable reasons, either before or after the above mentioned point of time, they were kept as close to them as possible. This time schedule was chosen in order to make easier and more precise the comparison of the surface wind distribution with winds aloft that are to be observed. In the moving observations of the wind, the fixed point was situated on the very summit of Mt. Kinpusan and observed every three minutes there. Twenty-six moving observation points, as shown in Fig. 3-a, were selected on the ridge and on the slopes on the both side of it, in consideration of the direction and grade of deformation. Owing to the circumstances of observers, several points among them were missed on each set of measurements.

In addition to these instrumental observations, in winter when icings were formed on the trunks of trees, we measured their direction by a compass, from which we inferred the distribution of surface wind direction.

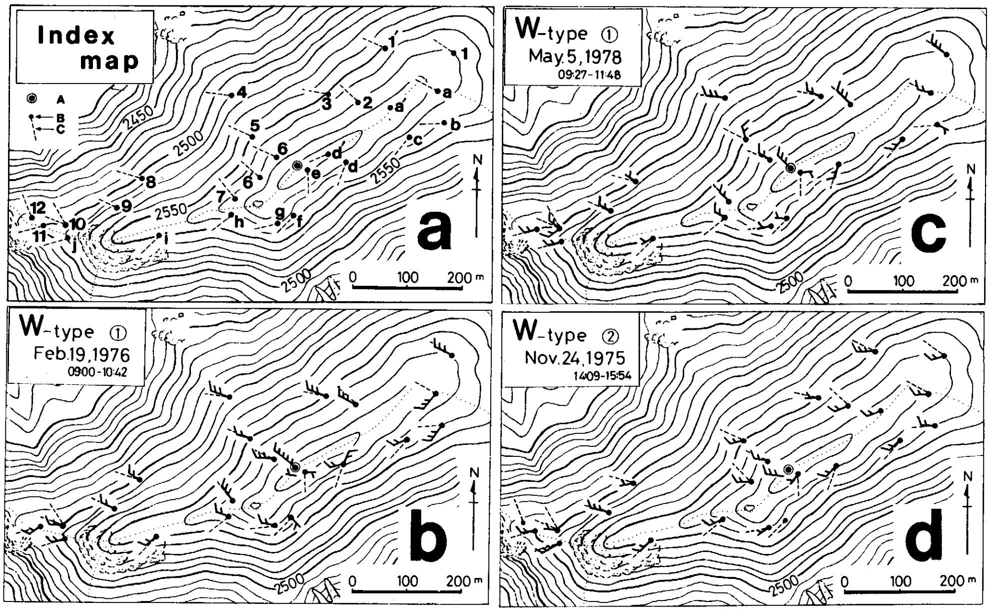

Fig. 3 The surface wind distribution (W-type)

a: Index map. A: fixed point; B: moving observation point; C: wind direction estimated from the wind-shaped tree (including more than one tree) at or near the point.

b-d: The surface wind distribution. Arrow shows the wind direction and wind speed. The number of its barb indicates the speed in the Beaufort's scale.

Table 1 A list of several data of the obtained surface wind distribution

No.	Observation date and time (moving observation by instruments)	Wind condition at fixed station (mean value)	Types of distribution-pattern	Weather condition[3]
①	1975.12.25 09:14—15:32	NW 8.5m/s	W—①	○, later⦶
②	1976. 2.19 09:00—10:42	NW 8.2m/s	W—①	◎
③	1978. 5. 4 13:24—15:24	NW-NNW 4.8m/s	W—①	◎
④	1978. 5. 5 09:27—11:48	NW 4.0m/s	W—①	◎
⑤	1978. 5. 5 13:00—15:09	NNW 4.7m/s	W—①	◎
⑥	1975.11.24 14:09—15:54	W-WNW 3.7m/s	W—②	○
⑦	1975.11.25 09:30—10:12	W 4.8m/s	W—②	○
⑧	1975.11.25 12:45—14:39	NW 5.3m/s	W—②	○
⑨	1975.11.23 09:39—11:57	SSE-S ——[2]	S—①	⊙
⑩	1975.11.23 13:21—15:33	SSE-S ——[2]	S—①	⊙
⑪	1976. 2.16 13:57—15:30	SSE-S 16.9m/s	S—①	●
⑫	1976. 2.18 10:06—11:33	SSE-S 22.2m/s	S—①	⊗
⑬	1976. 2.18 14:54—15:25	SSE 18.5m/s	S—①	●
⑭	1977. 9. 7 07:57—10:03	SSE-S 7.7m/s	S—①	⊙
⑮	1975.11.26 09:39—10:30	SE-SSE 3.3m/s	S—②	⦶
⑯	1976. 2.16 08:42—09:57	SSE-S 7.7m/s	S—②	◎or⊗or⊙
⑰	1976. 2.17 09:09—09:48	SSE 8.2m/s	S—②	◎, later⊙
⑱	1978. 5. 6 09:30—10:30	SSE-S 5.3m/s	S—②	⊙, later◎
⑲	1975. 8.18 08:41—10:40	SSE 5.1m/s	S—③	⊙
⑳	1975.11.24[1]	(not applicable)	N	

1) This date is that of the observation of icings formed on the tree trunks early in the morning.

2) Unobservable due to anemometer's trouble caused by icings

3) ○: clear ⦶: fine ◎: cloudy ●: rain ⊗: snow ⊙: fog

In this way, we obtained 29 examples of the wind distribution in six time's visit to the study area. Each of them was first checked if a range of wind directions at the fixed point was constant or not during its measurement, that is, if the distribution was a distribution dominated by a single synoptic wind condition or not. And then, those which show the valley breezes distribution patterns were excluded. Finally we obtained 20 examples of the wind distribution, each of which is considered to be dominated by a single synoptic wind condition. These examples are shown in Table 1. They include three examples (No. ⑦, ⑰ and ⑱), and some data at several points of which were cut, because they were measured after a range of wind directions had already shifted at the fixed point.

Features of surface wind distribution

With the wind direction distribution as a focal point of attention, these actual 20 wind distribution patterns were compared with that estimated from the deformation of trees.

Eight examples observed during cold season and in May were the cases in which the pattern of wind direction distribution agrees with that of the estimated from wind-shaped trees. These were symbolized as W-type. This agreement, however, was not found on both sides of the main ridge but on one side of it only. No synchronous observation was made in support of agreement; when agreement was found on one side, it was absent on the other. Therefore, W-type was classified into two types: one type in which the pattern of the wind direction distribution is almost the same as that of the estimated from the wind-shaped trees on the north slope (defined W-type ①) and the other type in which the pattern almost agrees with that of the estimated on the south slope(defined W-type ②). Typical examples of the two types are shown in Fig.3-b-d. W-type ① has several observation points whose wind directions agree with those estimated from the deformation there on the south slope, for example the points 11,i and j. On the north slope in W-type ②, each wind direction at most points deviates west to the wind direction estimated, except a few points. Moreover, as to the wind speed distribution pattern of W-type, the wind speed is on the whole greater on the north slope than on the south slope, in most of both W-type ① and W-type ②.

In addition to this W-type, two main types of patterns of the wind direction distribution were found.

One was the type in which southerly winds blow up on the S-facing slope, cross over the main ridge and extend to the north side of it. This was called S-type. In the S-type, each wind direction on the windward slope usually deviates several tens degrees counterclockwise from the estimated wind direction. S-type was mainly classified into three types: the first type in which up-slope southerly winds cross over the ridge, go round behind it and blow horizontally (along the contour line) on the

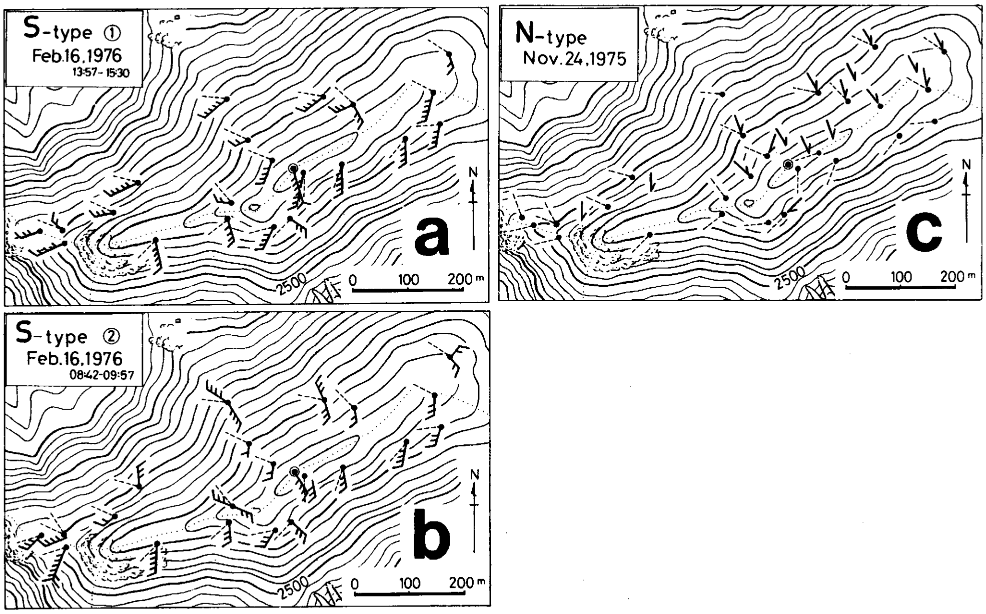

Fig. 4 The surface wind distributions (S-type and N-type)
In S-type of this Fig. 4 same as Fig. 3b-d. In N-type the wind distributions were estimated from the icings on trees.

N-facing slope (S-type ① Fig. 4-a), and the second type in which up-slope southerly winds blow over the main ridge and blow down along the north slope accompanying up-slope opposite winds to the lower part of this slope (S-type ② Fig. 4-b). Further, the third type in which the southerly winds are confined on the S-facing slope, and northerly or northeasterly weak winds are seen on the north facing slope (S-type ③, which is not shown here).

The other type was called N-type (Fig. 4-c). This was the type in which northerly winds, showing the deviation of several tens degrees clockwise in angle from the estimated wind direction at each observation point, blow up on the N-facing slope, cross over the ridge, go round behind it and blow horizontally on the S-facing slope. This appeared only once in our observations.

Moreover, it is noteworthy that all of the W-type pattern appeared under comparatively fair weather without precipitation (see the right end column in Table 1). On the other hand, the S-type occurred under the bad weather with rain or fog, or in winter occasionally with snow or icings.

Determination of synoptic wind condition and air flow patterns

As the next step, suitable synoptic wind conditions were examined, on the assumption that each type of patterns of the surface wind distribution appears under a specific wind aloft.

First we must decide which wind aloft data should be adopted out of those observed at four wind-aloft-observation-times (0300, 0900, 1500, 2100 JST), as the data which correspond to each type of patterns of the surface wind distribution. As applicable to instrumental observation, wind aloft data at 0900 JST or 1500 JST were adopted, because the surface wind observation was made at about in these times, as was stated previously. In regard to icings observation in No. ⑳ in table 1 (the observation of icings was carried out in the morning), the data at 0300 JST on that day were adopted, because the icings were considered to have been formed early in the morning of that day.

As to the wind aloft data, not actual observational winds but gradient winds were adopted. Then, gradient winds of two standard surfaces, the 700 mb surface (about 3,000 m a.s.l.) and 800 mb surface (about 2,000 m a.s.l.) were selected in consideration of altitude in the study area. To infer the gradient wind direction of the two surfaces, the contour lines on these surfaces chart were drawn for each observation time, by using the upper wind-and-pressure data observed at eight stations (Akita, Sendai, Wajima, Tateno, Hachijojima, Yonago, Shionomisaki and Hamamatsu). From the direction of such contour lines over the Chichibu Mountains, the gradient wind direction for each of the two surfaces was decided. When the direction cannot be decided precisely, a range of deviation of 10 to 30 degrees in angle was allowed. Moreover, the gradient wind velocity was calculated as the arithmetic mean of wind velocities at three stations (Wajima, Tateno and Hamamatsu).

Each type of patterns of the surface wind distribution was compared with each of these gradient winds of the two surfaces at the observation time adopted. In comparing them, the direction of gradient wind was in particular focused on, because the types of

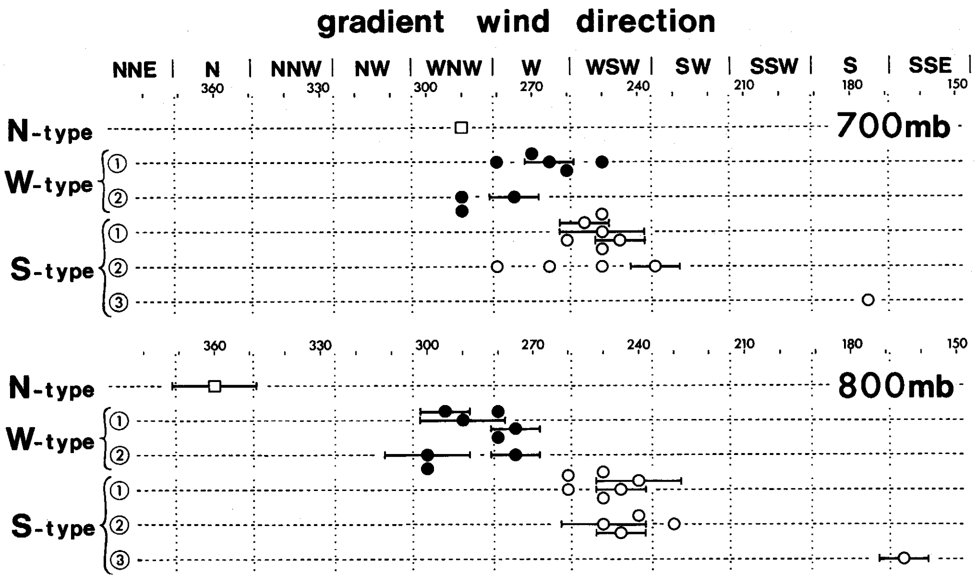

Fig. 5 The relationship between the gradient wind directions at two standard surfaces (700 mb and 800 mb) and the surface wind direction patterns in N-type, W-type and S-type

surface wind distribution patterns had been classified by direction. The relationship between the gradient wind directions of the two surfaces (700 mb and 800 mb) and the types of patterns of the surface wind direction has been ascertained, as shown in Fig. 5. At 700 mb, different types of surface patterns appear under the same gradient wind direction. At 800 mb, on the contrary, different types do not appear under the same gradient wind direction. Thus, the gradient wind direction at 800 mb was found to be more closely related to the type of patterns of the surface wind direction distribution. Hence the set of gradient wind direction of the 800 mb surface was chosen as the synoptic wind condition. Then, this was subsumed under the following three air flow patterns.

air flow pattern	range of the gradient wind direction at 800 mb	type of the pattern of the surface wind direction distribution
N	NW(N)——NE	N-type
W	W(N)——NW(S)	W-type
S	SE——W(S)	S-type

The range of gradient wind direction in the W air flow pattern was determined almost exactly by the actual range of directions in the eight examples. On the other hand, the eastern limit of the range in the S air flow pattern and the range in the N air flow pattern were much less determinate. The ranges in these air flow patterns therefore are somewhat arbitrary. Since, however, this indeterminacy is marginal in significance, we conclude that each type of patterns of surface wind direction distribution (N, W, S-type) corresponds to N air flow pattern, W air flow pattern, and S air flow pattern, respectively. That is, we conclude that each type appears under the corresponding air flow pattern, respectively.

In this connection, in the W-type pattern, the gradient wind direction does not show any systematic difference between W-type ① and W-type ②.

Occurrence frequency of each air flow pattern

As the first step in the third stage, the gradient wind directions of 800 mb in winter (Dec.-Feb.) and in summer (June-Aug.) for several years (1970/71-1974/75 in winter, 1971-1975 in summer) were decided from the direction of contour lines of 800 mb surface drawn by the same method as mentioned above. Then the occurrence frequency distribution of directions was calculated and the calculated values were aggregated for each air flow pattern. The results are shown in Fig. 6. The features of the frequency will be described in the next section; here let me point out only that the W air flow pattern has the highest frequency in winter and the S air flow pattern has it in summer.

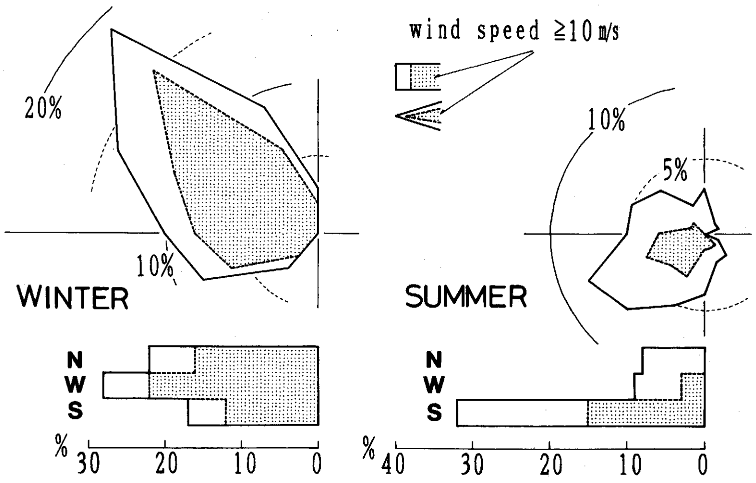

Fig. 6 The occurence frequency of th gradient wind directions (800 mb) and that of the three air flow patterns, in winter (Dic.-Feb.) and in summer (Jun.-Aug.)

5. Discussion

Climatic causes of the wind-shaped trees

Formative factor for the deformation

From the analysis in the previous section, we assume that the winds, concerning the formation of deformed trees, are those of the W-type surface wind distribution pattern, and that this type appears under the W air flow pattern of 800 mb. Then, the features of the winds as the formative factor must be described by analyzing the climatic features of the W air flow pattern.

As has been pointed out in Fig. 6, the season in which the frequency of the W air flow pattern attains to its maximum is winter. In winter, this air flow pattern was predominant. In summer, the frequency of the W air flow pattern is only less than one third of that of the S air flow pattern. These facts indicate that the prevailing winter winds essentially connect with the formation of wind-shaped trees in this area.

Then, what nature of the winter winds is it?

First, let us examine the weather condition accompanied by the W air flow pattern. From weather conditions of our surface wind observation, we can infer that the weather with the W air flow pattern is fair without precipitation. In order to confirm this inference, the above stated weather records in the manager's diary at the Kinpusan-*goya* for ten years (1970-1980, excepting 1978 for which the data were not available) were analyzed relating to each air flow pattern. The weather in the area was recorded every day from the last several days of April to the end of November. Midwinter weather records, however, were confined to the end of December and the beginning of January. To mention in detail, these records cover only five winters (total 44 days) when the hut was open in special. In order to supply the insufficient data, the records of ten years of November's were also analyzed as those of the winter season.

The results including the S and the N air flow pattern as well as the W are as follows:

air flow pattern	total frequency	without precipitation		with precipitation
		clear+fine	cloudy+foggy	
N	34	27 (79.4 %)	2 (5.9 %)	5 (14.7 %)
W	76	65 (85.5 %)	9 (11.8 %)	2 (2.6 %)
S	133	73 (54.9 %)	26 (19.5 %)	34 (25.6 %)

In the table, the cases that the gradient wind directions are from ENE to ESE (seven examples) and the cases that they were unable to be classified were excluded. This table evidently indicates that the W air flow pattern in most cases occurs accompanied by the clear or fine weather and without precipitation, just as we have inferred. The fair weather appears in relation mainly to the typical winter pressure pattern (the type of west-high, east-low) and partly to the pressure pattern of migratory high. The table also shows that about 80 % of winter precipitations occur in the S air flow pattern. These winter precipitations are brought almost by the passing lows along the Pacific coast of Japan or the front along the coast and partly by the coupled lows across Japan.

Next, we will investigate the temperature accompanied by the W air flow pattern. In order to infer these temperatures at the study area, 59 examples of the W air flow pattern out of two winters of 1973/1974 and 1974/1975 were selected. Then about each of samples isotherms on the 800 mb surface chart for 2100JST were drawn, and the temperature at the Chichibu Mountains from isotherms in the chart was read. As a result, the temperature on the 800 mb surface showed −7.9°C on the average and the temperatures of the 51 cases out of all were contained within the range from −5 to −14°C. Since the study area is higher than the average of 800 mb surface by about 500 meters in altitude, the air temperature of the study area is considered to be two to three degrees lower than these values.

In the light of these weather and temperature condition accompanied by the W air flow pattern, we can conclude that the hypothesis of "drier colder prevailing winter wind" was verified. That is to say, in subalpine zone belonging to the region of Pacific side climate, the drier colder prevailing winter winds without precipitation are the only essential wind factor for the formation of wind-shaped trees.

In this connection, Oka (1980) pointed out that the drier colder northwesterlies in winter are an important cause for his F type (this seems to correspond to Yoshino's type 2) deformation of *Larix leptolepis* around the tree line of Mt. Fuji, located in the region of Pacific side climate.

Process of deformation

From the following condition of temperature and snow cover in the study area, as well as the nature of the winds of the W-type, we can infer that the deformation trees are mainly connected with the desiccation damage, that is, the injury by evaporative stress under the freezing of soil or stem. Now, let us discuss this inference in some detail.

As to the freezing of soil in early winter in this area, we can estimate it by using the method proposed by Fukuda (1982). He claimed that the depth of the frozen soil layer (cm) in a snowy and cold area equals α (a parameter determined by the property of soil ranging from 2.0 to 4.0) times the square root of the value of freezing index (degree day). This freezing index indicates the accumulated absolute value of daily mean temperature below-zero. Here we need to accumulate it up to the time point just before the snow cover of 20 cm deep or more begins to continue for seven days or longer during the winter.

First, about the snow cover in the study area, we were able to obtain reliable information from the manager of the Kinpusan-*goya*. According to him, from the end of November or later time, the continuous snow cover is seen along the minor ridge from the hut to the summit on N-facing slope. The snow cover from that time, however, was usually only 10 cm deep, and it reaches at most 20–30 cm even early in January. Hence the snow cover there is considered to be maintained less than 20 cm deep till the middle of December in the average year.

As for the temperature during this scanty snow cover period in the area, Higuchi(1990)'s observation gives us useful information. He observed and graphed the air and soil temperature during the period including the cold season in 1986–87 at a bare site (2,715 m a.s.l.) on Mt. Hoozan, located about 35 km west-south-west of Mt. Kinpusan and belonging also to the region of Pacific side climate. The daily mean temperature of every day from October to December in 1986 was read from the graph in his paper. From these data, that of every day in this period in my study area was derived, considering the difference in altitude from his site. Then from these data derived, the freezing index value up to the middle of December was ascertained by calculation to be 98 degree days. Substituting this value into the Fukuda's formula above, we obtain the value of 20-40 cm as the frozen soil depth in the area. Actually, Shimizu (1983) reported that the fine debris layer under the blocks of an outcrop at the Kinpusan-*goya* was frozen hard (50 cm deep at least—according to Shimizu's private communication) early in November in 1980. Therefore the frozen depth should probably reach about 50 cm or more deep at least, by the middle of December in an ordinary year in the study area.

Now, thereafter, according to the manager, the snow cover attains a depth of about one meter with several snow falls, which are undoubtedly brought by the lows or fronts with the S-type pattern of surface wind distribution. Under this deep snow cover, the ground probably still remains frozen during winter and early spring, considering Kojima(1982)'s observation in Hokkaido. About this, it should be noted that even in the middle of May in 1981, the humic layer and moss on the blocks were observed to be still frozen 20-30 cm deep at a site (2,470 m a.s.l.) in the conifer forest on the north side of the main ridge through the summit of Mt. Kinpusan (according to Shimizu's private communication). Incidentally, the value of about one meter of the snow cover above has good correspondence to the average length—95 cm—of Part b in Fig. 2 of 36 trees along the minor ridge measured by me. The length of Part b of a wind-shaped tree is generally interpreted as the average snow depth (Yoshino, 1973).

In addition, Sakai (1968) reported that in a range of low temperature, including the temperature dealt with in my study, the stem 5-10 cm below the snow level is usually in a frozen state throughout the winter, when snow cover exceeds 30 to 50 cm.

Thus, in the study area the frozen state of the ground and/or that of the stems of trees is certainly maintained during winter. Therefore we reasonably conclude as follows. Under these conditions the water ascent in the stem of trees was blocked, during which process, the drier colder prevailing winter winds promoted the transpiration on the windward side of it. Hence the trees cannot make up the loss of water, in consequence, the desiccation damage is caused there.

Owing to this damage, the twigs and blanches on the windward side lose flexibility, dry out and sometimes die. In this way, they probably lowered the restoring force against the mechanical effects. As time goes by, they can therefore gradually be broken or trimmed; consequently they can be led to the asymmetric shape which we now recognize.

In these mechanical breakage processes, the wind pressure of the prevailing winter winds of W-type itself seems to have an important role naturally. In addition, the winter winds of the S-type accompanied by snow flake or icings and the winds of N-type or other season's occasional severe winds, in my opinion, also play a considerable part in the breakage process. These winds other than w-type, however, work effectively not on their windward side of trees, but only on the windward side of the prevailing winter winds of W-type. In other words, they only affect the side whose twigs or branches have suffered the desiccation damage, and consequently, have become susceptible to breakage. We infer the occurrence of these processes from the facts that the S-type and the N-type wind direction pattern are obviously different from the wind direction pattern estimated from the deformation.

Climatic meaning of the distribution of wind-shaped trees

According to the consideration above, the distribution of the wind-shaped trees shown in Fig. 1-b indicates, on the whole, that of the prevailing winter winds around the summit of Mt. Kinpusan. But we should note that strictly speaking, the map does not express strongly synchronous distribution.

As to wind direction, a distribution pattern that agrees with the estimated pattern from wind-shaped trees was found only on one side of the main ridge at any point of time. Either W-type ① or W-type ②, agreeing with that estimated only on one side, was observed, as shown in Fig. 3-b~d. The distribution pattern of W-type ① and W-type ②, however, may occur alternately during a short time. This is probably because there was no systematic difference in the gradient wind direction between these two types.

On the other hand, the difference between the deformation grade of the N-facing slope and that of S-facing slope roughly corresponded to the difference between the wind speeds on both slopes on W-type observation by instrument. Hence we can regard, on the whole, the distribution pattern of the deformation grade in Fig. 1-b as that of surface wind speed of prevailing winter winds. In discussing the micro-scale distribution of wind speed by this figure, however, the problem of synchronousness emerges, because the deformation is strongly connected with the desiccation damage. That is, the grade of deformation is considered to be related not only to the wind speed of prevailing winter winds but also to the freezing of the ground, to snow depth and to the effects of winter winds with precipitation or those of other seasons' winds. How quantitatively these factors take part in the grade of deformation of the wind-shaped trees, is the subject for a future study.

Examination of some previous studies

The results of my investigation described above considerably differ in the following three points from those of previous studies by others of wind-shaped trees (*Abies mariesii, Abies veitchii*) in the subalpine zone in Japan.

The first point is that in my view wind-shaped trees in the region of Pacific side climate are connected with the winter winds. On the other hand, Kai (1976) suggested that they were affected by spring-summer winds. In her study, she analyzed the direction of wind-shaped trees distributed along the summits from Mt. Kinpusan to Mt. Karisakarei (2,289 m a.s.l. located about 15 km east of Mt. Kinpusan) in the Chichibu Mountains, and the direction of deformations in the 15 regions other than the Chichibu Mountains alike. In short, because in the Chichibu Mountains deformations by southerly winds are predominant, she stated the above opinion. The selection of these data, which had been taken from her previous report (Kai, 1974), however, does not seem to be relied on. For example, the number of data used was only about 20 in the mountains and the estimated wind direction of Mt. Kinpusan was recognized only as SW. Moreover, southerly winds were interpreted only as the winds during warm season, without considering of the probability of winter-winds' deviation influenced by micro-scale topography.

Accompanying the first point, the second different point appears that in my observation only one type of wind-shaped fir trees is found in this area, and this corresponds to the Yoshino's type 2 (Yoshino, 1973). According to Yoshino, the type 2 is found mainly in subalpine zone of the Northern "Japan Alps," which is situated in the region of Japan Sea side climate with much snowfall in winter. On the other hand, he stated that the type 1, which means that the branches on the windward side are bent drastically to the leeward of trees, appears mainly in subalpine zone of the mountains in the region of Pacific side climate. He explained moreover that the type 1 is formed by the prevailing winds during their growing period. In Fig. 4 in Part II of his paper, the symbol showing a wind-shaped tree (the kind of the tree is unshown) of the type 1 is plotted in the *Pinus pumila* zone just below the summit of Mt. Kinpusan. According to my surveys, however, no conifer tree's deformation of this type was found around there.

The third point is as follows. In my opinion, the formation of the type 2 is indeed connected with winter winds, but the winds with precipitation are only the secondary factor. Yoshino (1973) pointed out, on the other hand, that this type is formed by winter winds carrying snow or frozen rain. As previously stated, these winter winds are considered to play a certain role in the mechanical breakage process. This is shown in the description (Yoshino, 1973) of the observation on Mt. Azumayasan, Central Japan, made just after a strong winter monsoon condition with precipitation, although the mountain observed was not located in the region of Pacific side climate. However, it should be emphasized again that these winter winds with precipitation do not work on trees with breaking effect until they suffered the desiccation damage.

From these discussions described in the above, I am of the opinion that their explanations of the distribution of the types of wind-shaped trees and their causes are necessary to be reconsidered.

Incidentally, in the Alps of Europe and the mountains of the Continent of North America, for example, the formation of the wind-shaped trees in subalpine zone has been also considered generally to closely relate to the desiccation damage (for example, Aulitzky, 1963; Wardle, 1968). It seems to be of interest that even in Japan where generally the density of snow is comparatively high, the snow and icings have less influence on the deformation of trees.

Shimagare **phenomenon**

As to the *Shimagare* phenomenon in the Chichibu Mountains, some papers have been given (Iwaki and Totsuka, 1959; Yoshino, 1976; Kai, 1974). In these studies, the directions of movement of the *Shimagare* stripes have usually been estimated from the pattern of the stripes. Kai (1974) pointed out that this directions agree with leeward directions of the winds estimated from wind-shaped trees there, observing some of the *Shimagare* zones from Mt. Kinpusan to Mt. Karisakarei. However, on the south slope in the study area, the directions of their movement (N or NNE) deviate obviously from the leeward directions of winds (ENE-ESE) estimated from deformations found near the *Shimagare* area (Fig. 1-b). The deviation between these two directions has been recognized also in the Oku-Nikko Mountains and the Kita-Yatsugatake Mountains, Central Japan, for example (Oka, 1983). This deviation undoubtedly indicates that the winds connecting with the movement of *Shimagare* stripes are different from those with the formation of wind-shaped trees.

Now, we can reasonably infer that the movement of the stripes is strongly connected with warm-season winds in this area. This is because the directions of movement agrees with the leeward direction of winds found near the *Shimagare* area in the S-type wind distribution pattern; and in summer this S-type corresponding to the S air flow pattern attains its highest frequency. In my data we cannot determine what kind of winds they are in detail. These facts above, however, support the advantageous opinion in which the winds during warm season are regarded as the cause of the movement of *Shimagare* stripes (for examples, Yoshino, 1976; Oka, 1983).

The data of wind-shaped trees used for Kai's study above were, in my opinion, too small in number and were only those from the narrow area just below the main ridge. Therefore, there still remains some question about her discussion of the relation between wind-shaped trees and *Shimagare* phenomenon which, on the other hand, extends down to the lower part of the slopes. By using only a small number of general-survey data of wind-shaped trees, it is extremely difficult to examine the climatic causes of wind-shaped trees, or the relation between the wind-shaped trees and *Shimagare* phenomenon, as this paper is trying to do. We must discuss this on the basis of detailed data such as we have used in this paper.

6. Conclusion

We have examined the climatic causes of the wind-shaped fir trees in the region of Pacific side climate, selecting the area around the summit of Mt. Kinpusan as a study area. The results obtained are summarized as follows:

1) As to the shape of the deformation in this area, only the type corresponding to Yoshino's type 2 (the branches and twigs on the windward side are injured mechanically) is found. The deformation belonging to the type 1 of his (the branches and twigs on the windward side are bent to the leeward of the tree) is not observed there.

2) The drier colder winter winds, namely the prevailing winter winds there, are the only essential wind factor for the formation of the type 2 of wind-shaped trees.

3) In the light of the nature of these winds and the condition of temperature and snow cover in the area, the process of deformation is considered to have close connections with the desiccation damage.

4) The winter winds with precipitation or icings play only the secondary role in their formation. The summer winds regarded as the influential factor for wind-shaped trees in the region of Pacific side climate in previous studies also play the secondary role in it.

5) The distribution pattern of wind-shaped trees obtained, indicates, on the whole, that of the prevailing winter winds. Strictly speaking, however, it must be noted that

it does not express strongly synchronous distribution.

Thus, we conclude that the hypothesis of "drier colder prevailing winter wind" suggested in the previous paper (Ogawa, 1974) was verified.

Moreover, considering the result of the previous study in the southern ridge of Ozegahara together with our result above in Mt. Kinpusan, we also conclude as follows. Wind-shaped trees of fir such as *Abies mariesii* and *Abies veitchii* in subalpine zone, whether the zone belongs to the region of Pacific side climate or to that of Japan Sea side climate, are formed essentially by the drier colder winter winds, having close connections with the desiccation damage.

Furthermore, the directions of movement of *Shimagare* stripes, found on the south slope in this area, does not agree with leeward direction of winds estimated from the wind-shaped trees standing near these stripes. These moving directions agree with those of winds prevailing in summer in the *Shimagare* area. These facts support the advantageous opinion that the warm-season winds cause the movement of its stripes.

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