J Geophys (1986) 59:67–72

Journal of Geophysics

Absolute intensity of daytime whistlers at low and middle latitudes and its latitudinal variation

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Abstract. The statistical study on the field intensity of daytime whistlers at low (geomag. lat. 25°) and middle (35°) latitudes has been made, based on a lot of data obtained by the field-analysis direction finding system based on the simultaneous measurement of two horizontal magnetic field components and one vertical electric field component. At low latitude, the maximum absolute intensity is estimated to be 250 μV/m, while the corresponding maximum intensity at middle latitude amounts to 600 μV/m, being about 2.4 times that at low latitude. This latitudinal variation of daytime intensity is interpreted in terms of the joint influence of (a) source activity, (b) magnetospheric propagation effect and (c) ionospheric transmission loss. As the result, it is found that whistlers at each station are attributed to ducted propagation in the magnetosphere and have exited the ionosphere close to each observing station, as determined by the direction finding results. Furthermore, the cloud distributions observed by meteorological satellites have yielded that the duct entrance point of whistlers at each station fall within the active thunderstorm region. Hence, we can conclude that daytime whistlers are originated in the active thunderstorms in each conjugate region, are trapped in field-aligned ducts and followed by nearly the vertical exit from the ionosphere at each station. Finally the latitudinal difference of the intensity is satisfactorily interpreted in terms of the difference in the ionospheric transmission loss on the assumption of the same source intensity at each conjugate point and of no amplification in the magnetosphere.

Key words: Whistler – Magnetosphere – Absolute intensity – Direction Finding – Ducted propgation – Thunderstorm Activity – Ionospheric transmission loos

1. Introduction

The measurement of absolute intensities of VLF waves including whistlers and VLF/ELF emissions having propagated through the magnetosphere provides useful information not only on their propagation characteristics such as the ionospheric absorption and magnetospheric propagation (Helliwell, 1965; Hayakawa and Tanaka, 1978), but also on the wave amplification as a consequence of wave-particle interactions (Helliwell et al. 1973; Lohrey and Kaiser, 1979; Carpenter and LaBelle, 1982).

The present paper is concerned with the measurement of field intensity of whistlers. The apparent field strength of a whistler can be measured in a few ways. If the whistler is very strong, it is sufficient simply to record the amplitude as a function of time. From this record, the maximum, minimum and average values are readily be obtained (Helliwell, 1965). Another method, less quantitative, is to match an artificially generated whistler of known amplitude aurally with the natural whistler in question (Iwai and Outsu, 1958). The absolute intensities of whistlers cannot be accurately estimated unless both the wave normal direction and wave polarization are specified, and the measurement of them essentially requires the adoption of the direction finding. During the last decade, several kinds of VLF direction finding methods have been proposed (Tanaka, 1972; Cousins, 1972; Bullough and Sagredo, 1973; Tsuruda and Hayashi, 1975; Tanaka et al., 1976; Okada et al., 1977, 1981; Leavitt et al., 1978; Ohta et al., 1984). The results on the ionospheric exit regions have been extensively utilized to study the whistler propagation mechanism and duct properties (Matthews et al., 1979; Lester and Smith, 1980; Hayakawa et al., 1981a, b; Strangeways et al., 1983) and also the magnetospheric plasma dynamics (Sagredo and Bullough, 1973; Carpenter, 1980). However, reports are as yet very lacking on the absolute intensity of whistlers, because most of the direction finding systems except those by Okada et al. (1977, 1981) and Ohta et al., (1984) are only intended to find the wave normal directions without any interest in wave polarization.

The present paper deals with the measurement of the absolute intensity of whistlers as estimated by our field-analysis direction finding method based on the simultaneous measurement of two horizontal magnetic field components and a vertical electric field component (Okada and Iwai, 1980; Okada et al., 1981; Ohta et al., 1984), which determines not only the wave normal direction, but also the wave polarization. The measurements have been made at two different geomagnetic latitudes; a low-latitude station of Yamaoka (geomag. lat. 25° N) and a middle-latitude station of Moshiri (35° N), and we restrict ourselves to daytime whistlers because there exist many unsolved factors in the propagation of nighttime whistlers (Hayakawa and Tanaka, 1978). The intensity at each station has been presented in Sect. 2 and 3, respectively. Section 4 describes the latitudinal variation of the whistler intensity and the

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physical implications are discussed in terms of the joint influence of the source activity and the ionospheric and magnetospheric propagation characteristics.

2. Whistler intensity at Yamaoka (geomag. lat. 25° N)

The direction finding measurement at Yamaoka is intended to be fully automatic at a specific frequency of 5 kHz (Ohta et al., 1984) and the measurement has been continued since December, 1981. We have selected only events of high whistler activity (and, in turn, high intensity) and the summarized results are presented in Fig. 1. The data for these daytime events are based on nine events (the total number of whistlers used in deriving Fig. 1 is about 180.) and the local time (L.T.) of those events falls in the L.T. interval from ~15 h–~19 h (Hayakawa et al., 1985). The duration of all of the events is not larger than 2 h (Ohta et al., 1984; Hayakawa et al., 1985), those kind of occurrence burst being considered to be attributed to the life of a single duct as found by Hayakawa et al. (1983). The daytime intensity exhibits a relatively flat distribution in a range from 50–150 μV/m with a maximum occurrence at 100–125 μV/m. Then, the occurrence distribution of the intensity shows a decrease above 150 μV/m, and the peak intensity we have recorded is 225–250 μV/m.

Previously, Okada et al. (1977) carried out the field-analysis direction finding at Takayama (25°) very close to Yamaoka, but the observation period was too short to have a statistical study such as done in the present paper. They have succeeded in measuring the absolute intensity for a few whistlers during the most active period over a few days' observation interval. Their peak measured intensity at day was about 200 μV/m, which is found to be in good agreement with the present result.

As the measure of intensity, we use two quantities; one is the maximum intensity we have recorded and the other the intensity with maximum occurrence, which are 250 μV/m and 100–125 μV/m, respectively, at Yamaoka.

3. Whistler intensity at Moshiri (geomag. lat. 35°)

Although the direction finding at Moshiri was not automatic, the timing for the direction finding was made by monitoring the auxilliary real-time whistler analyzer (Okada et al., 1981; Hayakawa et al., 1983) in order to acquire as much useful direction finding data as possible. The observation was carried out for two months; January and February, 1978. The percentage occurrence of the field intensity of the most active daytime event; 22 January, 1978 (15:10–18:07 h L.T.) among the two months' observation period, is presented in Fig. 2. The total number of whistlers for this event amounted to more than two hundred, enabling us to have a statistical significance. The observing frequency is 5.6 kHz.

The figure indicates that a majority of whistlers have the field intensity in a range from 100 to 300 μV/m, and the most probable intensity is 250–300 μV/m. Furthermore, the number of whistlers become depleted sharply above the intensity of 300 μV/m, and the maximum intensity recorded at Moshiri is 600 μV/m.

Now we compare the maximum intensity (600 μV/m) and the intensity with maximum occurrence (250–300 μV/m) at Moshiri with the corresponding quantities at Yamaoka in Section 2. The maximum intensity at Moshiri is found to be 2.4 times that at Yamaoka, and the most probable intensity at Moshiri is again about 2.4 times that at Yamaoka. No matter whether we adopt the maximum recorded intensity or the most probable intensity, the intensity at Moshiri is always about 2.4 times larger than that at Yamaoka.

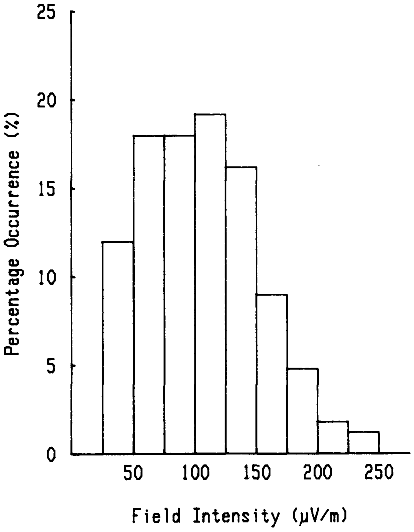

Fig. 1. Percentage occurrence of field intensity of daytime whistlers at Yamaoka (geomag. lat. 25°). The observing frequency is 5.0 kHz

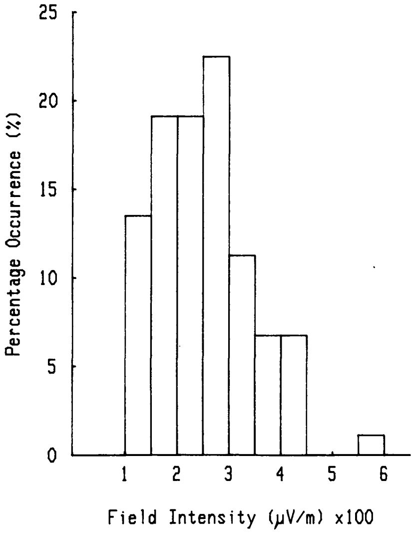

Fig. 2. Percentage occurrence of field intensity of daytime whistlers at Moshiri (geomag. lat. 35°). The observing frequency is 5.6 kHz

4. Latitudinal variation of the daytime whistlers intensity

The important factors determining the observed whistler intensity include, (a) the source activity of source intensity, (b) the ionospheric transmission loss passing through the ionosphere and (c) the propagation loss and/or amplification in the magnetosphere.

First we are concerned with the characteristics of daytime whistlers at Yamaoka in Sect. 2. The third point (c) on the propagation in the magnetosphere is studied first. The results of direction finding studies for all of those events have yielded that the ionospheric exit points are located

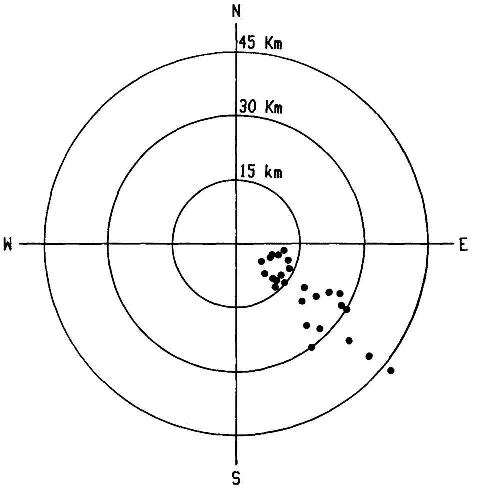

Fig. 3. An example of ionospheric exit points of daytime whistlers observed at Yamaoka at 16:00–16:50 h L.T. on 16th January, 1982

close to the observing station and also that those whistlers are identified as being attributed to the propagation entrapped in field-aligned ducts (Ohta et al., 1984; Hayakawa et al., 1985), so that we have negligibly small propagation loss in the magnetosphere. An example of the direction finding result on the ionospheric exit points of whistlers is illustrated in Fig. 3 for the event of ~16 h L.T. on 16th January, 1978. We now mention the amplification in the magnetosphere. Taking into account the results by Carpenter and LaBelle (1982) and Lohrey and Kaiser (1979), the whistler amplification seems to be possible even at $L<2$, but only during major magnetic disturbances and for a number of days following those disturbances. However, the whistler data in the present study are not obtained during the severe magnetic disturbances, which enables us to consider that the amplification did not take place, at least, for our events analyzed. This supposion seems to be furthermore supported by the success of our interpretation of the latitudinal dependence of whistler intensity in terms of the ionospheric absorption loss alone, to be discussed below. Then, the source activity (a) at the duct entrance point in the opposite hemisphere is examined by means of the cloud distribution observed by the Japanese meteorological satellite, GMS 2. The cloud distribution for the event at the time close to the event in Fig. 3, is illustrated in Fig. 4 as an example, from which we understand that the duct entrance point falls within the active thunderstorm region. These kinds of case studies have given strong support to the similar conclusion based on the statistical map of atmospheric intensity (Tanaka and Hayakawa, 1980). Furthermore, we have examined the cloud distributions during more than 6 h including the relevant whistler active period, and it is found that the duct entrance point is always located in the active thunderstorm region during the relevant time, and hence we can conclude that the duration of whistler activity of the order of a few hours (1–2 h) is not controlled

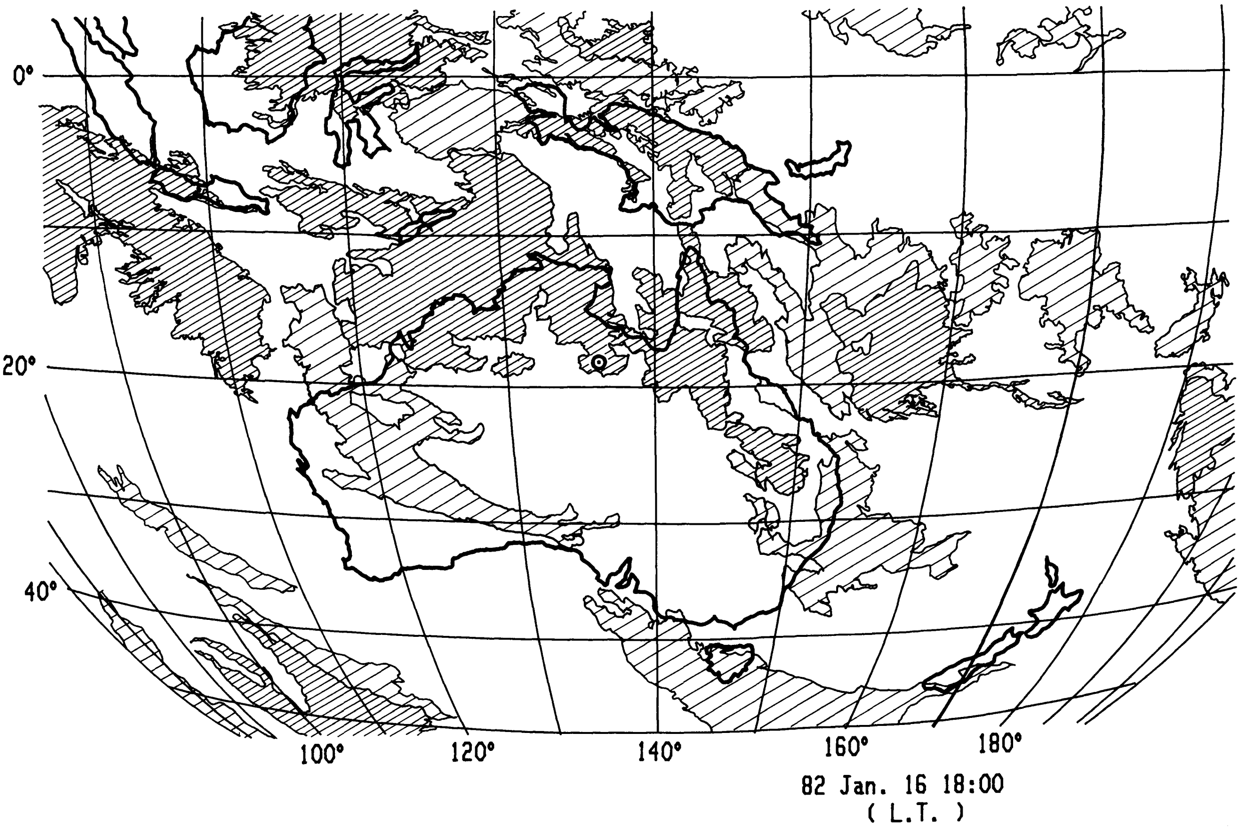

Fig. 4. The cloud distribution around the conjugate region of Yamaoka at 18:00 h L.T. on 16th January, 1982, being closest to the whistler active period in Fig. 3. *Densely-hatched region* indicates the active thunderstorm region, while *hatched region* the less active region. *The dot with a circle* indicates the conjugate point of Yamaoka, calculated by using the IGRF (1975) model

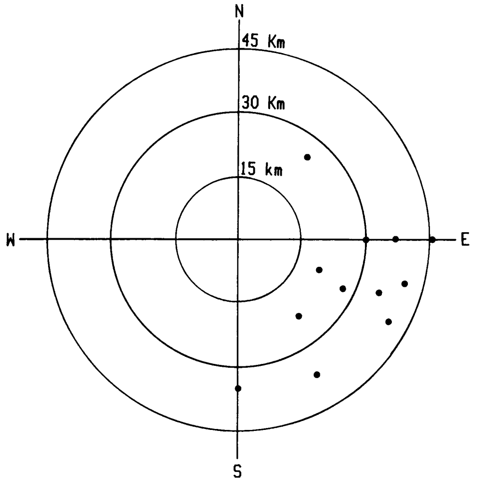

Fig. 5. Distribution of the ionospheric exit points of daytime whistlers observed at Moshiri during the most active period (16:00–16:05 h L.T.) on 22nd January, 1978

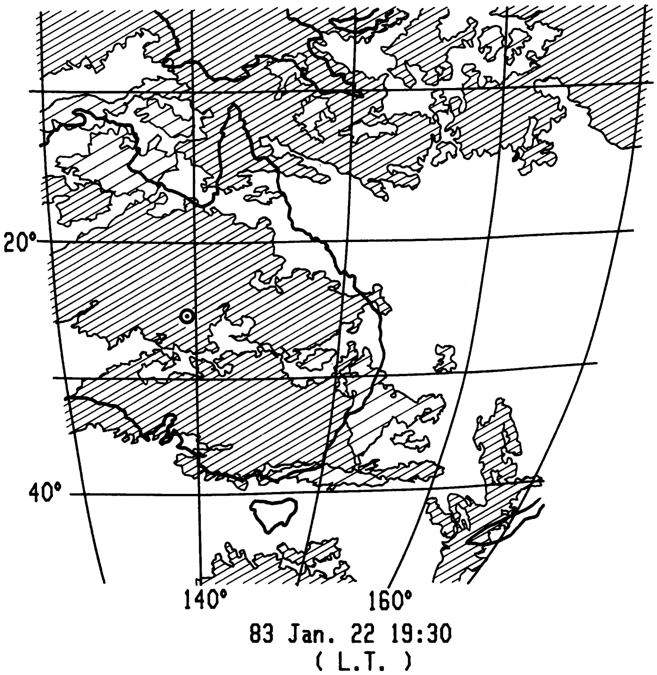

Fig. 6. Cloud distribution at 19:30 h L.T. on 22nd January, 1978, closest to the most active whistler period in Fig. 5

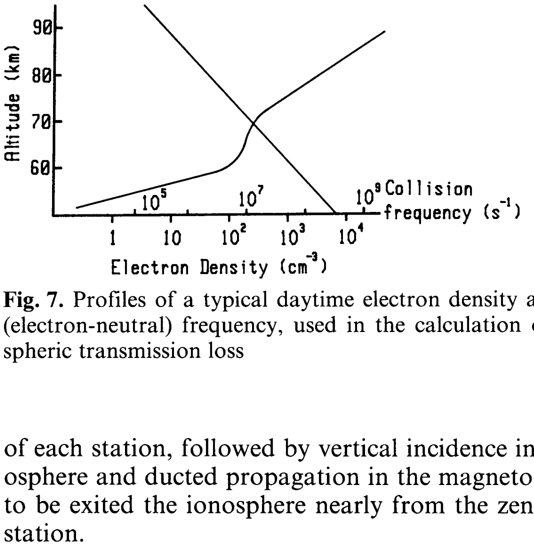

Fig. 7. Profiles of a typical daytime electron density and collision (electron-neutral) frequency, used in the calculation of the ionospheric transmission loss

by the source activity, but by the duct lifetime itself, lending further support to the previous finding (Hayakawa et al., 1983; Ohta et al., 1984; Hayakawa et al., 1985). These facts have been extensively confirmed to be valid for all other events.

Next we pay attention to the characteristics of daytime whistlers at Moshiri in Section 3. The direction finding study by Hayakawa et al. (1981a) has indicated that whistlers for the event studied in the present paper have exited the ionosphere very close to the observing station of Moshiri, as shown in Fig. 5, where the ionospheric exit points are located at the time of maximum whistler activity (16:00–16:05 h L.T., 22 January, 1978). Consideration of those results suggests ducted propagation of whistlers in the magnetosphere (Hayakawa et al., 1985), as in the case of Yamaoka. Hence, we are able to assume no propagation loss in the magnetosphere. Furthermore, the magnetospheric amplification is not considered on the same reason mentioned in the previous paragraph of the observation at Yamaoka. Then, the corresponding source activity at the duct entrance region for this event has been examined by using the cloud distribution in Fig. 6, observed by the NOAA 5 satellite at the time (19:30 h L.T.) closest to the whistler peak (~16 h L.T.), though a few hours apart from the whistler peak. At 19:30 h L.T. the whistler activity was still not small, as seen in Hayakawa et al. (1981a). The duct entrance point is found to be located at the edge of the active thunderstorm region extending to the west. Although we have examined the NOAA cloud pictures before and after 19:30 h L.T., no maps have been available, on the cloud distributions around the conjugate point of Moshiri. Hence, we cannot say definitely that the duration of whistler occurrence of a few hours in this event is again attributed to the formation and decay of a duct, but it would be reasonable to accept it, from the considerations for the case of Yamaoka. We should add that the difference in observing frequency does not make any significant difference in the ducted propagation in the magnetosphere.

From the above considerations, daytime whistlers observed at Yamaoka and Moshiri are identified to originate in the active thunderstorm region at the conjugate point of each station, followed by vertical incidence into the ionosphere and ducted propagation in the magnetosphere and to be exited the ionosphere nearly from the zenith at each station.

The second factor (b) of the ionospheric transmission loss has been theoretically calculated by means of the full-wave computation by Pitteway and Jespersen (1966). Figure 7 gives a typical daytime electron density profile and the typical collision frequency profile. These profiles are assumed to be independent of geomagnetic latitude, but the gyrofrequency is varied with latitude according to the dipole model. Figure 8 illustrates the latitudinal dependence of the ionospheric transmission loss on the assumption of vertical incidence just for one transit through the ionosphere. One can find that this vertical incidence is validated at the duct entrance and at the wave emergence, as mentioned above. The figure indicates that the difference in the ionospheric transmission loss at Moshiri (35°) and Yamaoka (25°) is 4 dB, taking into account the difference in observing frequency, and the total difference is 2 × 4 dB = 8 dB, implying that the intensity at Moshiri is about 2.5

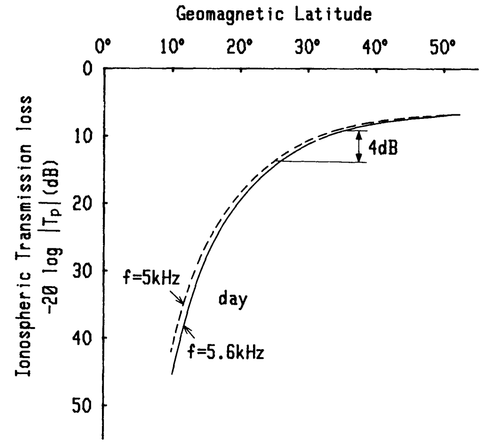

Fig. 8. Latitudinal dependence of the ionospheric transmission loss for vertical incidence (one transit through the ionosphere). T_p is the transmission coefficient of the penetrating mode defined in Pitteway and Jespersen (1966)

times that at Yamaoka, on the assumption that the source intensity is the same at the conjugate point of each station. This theoretical prediction seems to be in excellent agreement with the experimental findings summarized at the end of Sect. 3, and this enables us to suppose that the source intensity is not different at the conjugate points of two stations, Moshiri and Yamaoka. Furthermore, it is known that the source spectrum exhibits a negligibly small difference between 5.0 and 5.6 kHz (Taylor, 1963) and so the difference in observing frequency is considered to have no influential effect.

Finally, we briefly comment on the possibility of whistler amplification at middle and low latitudes. Our previous whistler studies (Hayakawa et al., 1969; Tanaka and Hayakawa, 1973a, b; Hayakawa and Tanaka, 1978) have yielded that the occurrence rate of whistlers increases abruptly from the onset of a magnetic storm and exhibits a maximum a few days after the storm. This experimental fact seems to be consistent with the property of whistler amplification reported by Carpenter and LaBelle (1982), which may lead us to suppose that those delayed enhanced occurrence (in turn, the intensity) of whistlers is indicative of such an amplification in the magnetosphere at $L<2.0$. In order to study these in a quantitative wave, we plan to make an application of the simultaneous measurement of absolute intensity of a causative atmospheric and the resultant whistler, simultaneous to the measurement of the corresponding particle precipitation based on the measurement of the phase variation of subionospheric VLF waves such as done by Lohrey and Kaiser (1979) and Carpenter and LaBelle (1982).

Acknowledgement. The authors wish te express their sincere thanks to Prof. J. Ohtsu of Nagoya University and Prof. H. Eguchi of Chubu University for their useful discussion. Thanks are also due to Japanese meteorological Agency for supplying the cloud maps by the GMS 2 satellite and we are indebted to Dr. D. Thiel of Griffith University, Australia who has obtained the NOAA cloud maps from Australian Meteorological Agency. The present work is partly supported by Japan Society of Promotion of Science and also partly by Takeda Science Foundation, to which we are grateful. Finally, we appreciate the continual encouragement of Prof. A. Kimpara, Emeritus Professor of Nagoya University.

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Received July 31, 1985; Revised version September 6, 1985;
Accepted October 1, 1985