Regional division of snow-depositional environments and metamorphism of snow cover in plain areas along the Japan Sea coast

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Abstract The objective of this study was to determine the division of snow-depositional environments based on certain snow characteristics observed in plain areas along the Japan Sea coast. Snow surveys carried out during the two winter monsoon seasons in 1986 and 1988, permitted the measurement of snow depth, the water equivalent of snow, snow stratigraphy, snow type, snow temperature and Ram hardness. The areas were divided into 11 regions according to significant changes in snow cover characteristics. Most of the boundaries between the regions were consistent with the topographical features, such as mountain ranges, peninsulas and bays, which suggests that the characteristics of snow cover are controlled not only by meteorological conditions after snow deposition but also by the regional characteristics of snowfall phenomena. By comparing the observed snow type with meteorological data, two indexes for indicating the degree of snow metamorphism were introduced. A snow metamorphism diagram showing the relationships between the predominant type of snow metamorphism and meteorological conditions was constructed by use of the indexes.

INTRODUCTION

The winter climate of Japan is dominated by the northwesterly monsoon, which brings heavy snowfall to the areas facing the Japan Sea. The areas span a wide range of latitude from 35 to 45°N, and the distance along the coast is more than 1500 km.

The characteristics of snow cover depend mainly on the degree of metamorphism controlled by the climatological and meteorological conditions in winter. The conditions are defined as "snow-depositional environments" in this paper. The characteristics of snow cover should vary according to the location of snow-depositional environments. Snow surveys have been conducted in Hokkaido and Niigata Prefecture, Japan, over a wide area from the viewpoint of the regional division of snow-depositional environments (Endo *et al.*, 1976; Watanabe *et al.*, 1976; Yamada & Ikarashi, 1980). However, because of logistical difficulties, the overall snow-depositional environments throughout the heavily snow-covered areas in Japan have not yet been sufficiently elucidated using the same criteria. Since snow cover is believed to exert an influence on the distribution and speciation of plants (Uemura, 1992), the regional division of snow-depositional environments is considered to be very important for a fundamental study of the relationships between snow cover and ecosystem structure.

In addition, the metamorphic processes determining snow type are largely governed by the temperature distribution in snow cover. Thus, the type of snow, including the shape and size of snow particles, depends on the thermal history of snow cover from the time of deposition. The processes can be classified into three types: "temperature-gradient metamorphism", "equi-temperature metamorphism" and "melt-freeze metamorphism" (Sommerfeld & La Chapelle, 1970). The first and second occur under conditions of sub-freezing temperature resulting in the formation of depth hoar and fine-grained compact snow respectively, while the third occurs when the meltwater percolates into snow cover resulting in the formation of coarse-grained granular snow. To understand snow cover variation and snowmelt runoff, it is necessary to clarify the quantitative relationships between the predominant type of metamorphism and the meteorological conditions affecting the snow cover.

In order to divide snow-depositional environments using regional shifts in snow characteristics in plain areas along the Japan Sea coast (Hokkaido to Kyoto Prefecture), snow surveys were carried out during two winter monsoon seasons in 1986 and 1988. By comparing the observed snow type with meteorological data, relationships between the predominant type of metamorphism and meteorological conditions were discussed.

SITES AND METHODS OF INVESTIGATION

Observations were made in plains and basins below 200 m a.s.l., from 10 to 22 February 1986 and from 17 February to 4 March 1988, when the depth of snow cover reached its maximum and marked differences in snow characteristics were found from region to region. Observation sites were selected in open and comparatively flat spaces, free from any obstruction to snow deposition. The number of sites was 38 in 1986 and 97 in 1988. The main observations were snow depth, the water equivalent of snow, snow stratigraphy, snow type, snow temperature and Ram hardness. The measurements of water equivalent of snow and Ram hardness were made using a cylindrical snow sampler with an inner area of 20 cm^2 and a Swiss rammsonde respectively. The Ram hardness was measured only in 1988. Observations of snow stratigraphy and snow type were made mainly by the snow pit method at sites where the snow cover was comparatively thin. However, because of the limitation of time to conduct moving observations over a wide area during a short period, the cores obtained by the cylindrical snow sampler were also used for observation at some sites. The observational data has been reported in detail by Kawashima *et al.* (1987, 1988).

REGIONAL DIVISION OF SNOW-DEPOSITIONAL ENVIRONMENTS

Areal distributions of the physical properties of snow cover in 1988 are shown in Fig. 1. The mean snow density was obtained by dividing the water equivalent of snow by the snow depth. Figure 2(a) shows the distributions of sites where solid-type or skeleton-

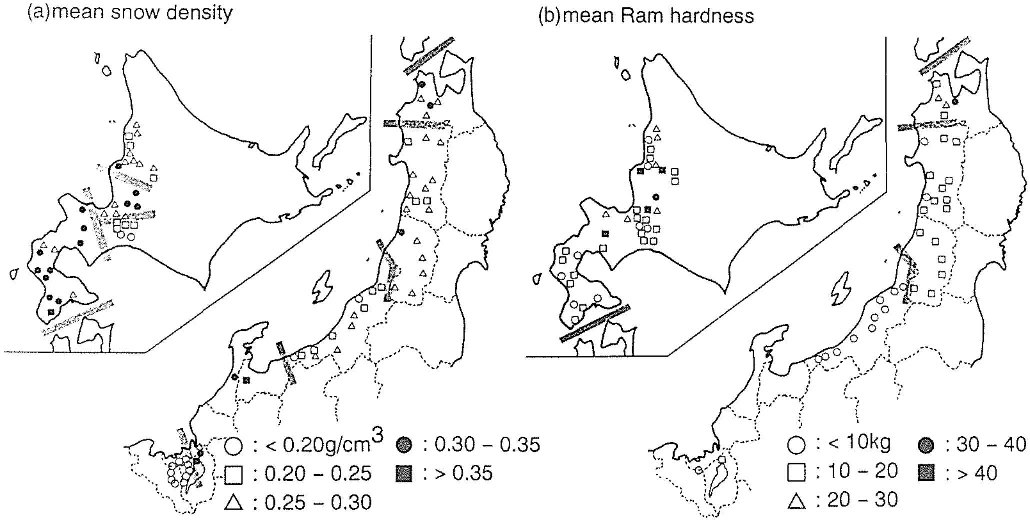

Fig. 1 Areal distributions of (a) mean snow density and (b) mean Ram hardness observed in 1988.

type depth hoar were found. The sites are concentrated in the northern regions characterized by the relatively cold climate. The ratio of granular snow thickness to the total snow depth was calculated at every site; the distribution is shown in Fig. 2(b). Discontinuities in the distribution pattern are seen at the zones indicated by shadowed lines.

Linear relationships are observed between snow depth and the water equivalent of snow from region to region (Fig. 3). Nishimura *et al.* (1980) also indicated that the

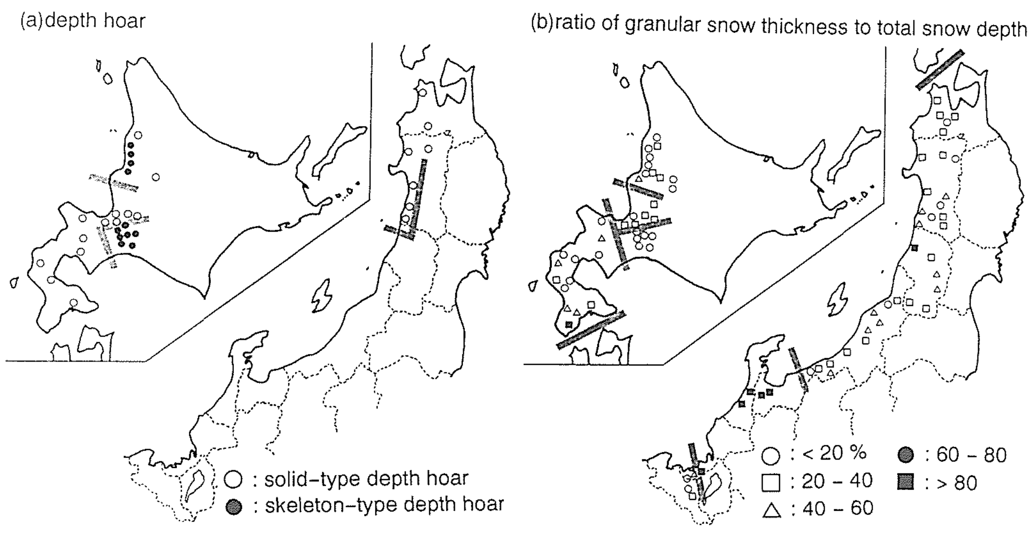

Fig. 2 Areal distributions of sites where solid-type or skeleton-type depth hoar were found (a) and the ratio of granular snow thickness to the total snow depth (b) observed in 1988.

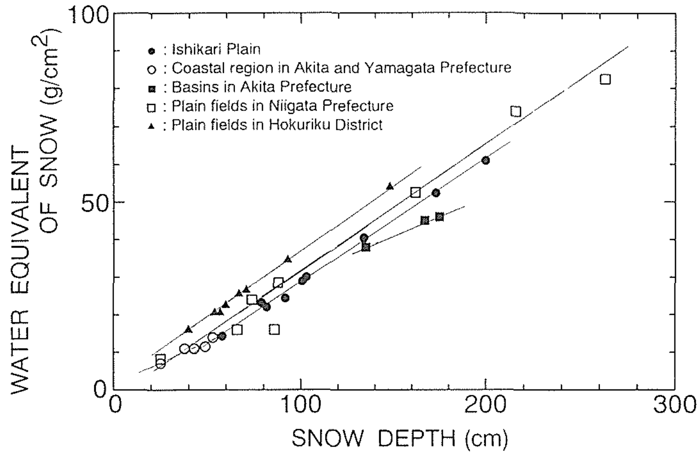

Fig. 3 Relationships between snow depth and the water equivalent of snow observed in 1986.

linearity is conserved through the snow season on the slope of Mt Asahidake, Hokkaido, although the slope of the relationship changes with the lapse of time. This phenomenon may be attributed to the consistent effects of the same snow-depositional environments on snow metamorphism over the whole region. That is, the linearity is considered to be a characteristic of a region which is subject to the same snow-depositional environments.

According to the significant shifts in snow characteristics, obtained from the physical properties of snow, type of snow texture and the relationships between snow depth and the water equivalent of snow, the areas observed in 1988 can be divided into 11 regions from the viewpoint of snow-depositional environments. These are: the northern part of Hokkaido (north of Mashike Massive), the southern part of Hokkaido (Oshima, Hiyama and Shiribeshi Districts), the Ishikari Plain, the Yufutsu Plain, the western part of Aomori Prefecture, the coastal region in Akita and Yamagata Prefectures, the basins in Akita Prefecture, the basins in Yamagata Prefecture, the plain fields in Niigata Prefecture, the plain fields in the Hokuriku District (Toyama, Ishikawa and Fukui Prefectures) and the coastal region along the Wakasa Bay (Fig. 4). This division is not inconsistent with the distributions of snow characteristics obtained in 1986.

Other regional divisions led by temporal and areal distributions of precipitation during the winter monsoon season, which were obtained by Suzuki (1962) and Wakisaka (1986), are in good agreement with the regional division of snow-depositional environments presented in this study. It strongly suggests that the evolution of snow characteristics is dependent on the regional characteristics of snowfall phenomena as well as meteorological conditions after snow deposition. In fact, most of the boundaries of snow-depositional environments are consistent with the topographical features, such as mountain ranges, peninsulas and bays. Previous investigators found out that the cloud movement in the winter monsoon seasons was subjected to the above topographical features, which exert an influence on the wind system. As a result, the snowfall phenomena shift regionally (e.g. Yagi & Uchiyama, 1983; Kikuchi *et al.*, 1987). This suggests that the regional division of snow-depositional environments may depend to a marked extent on topography.

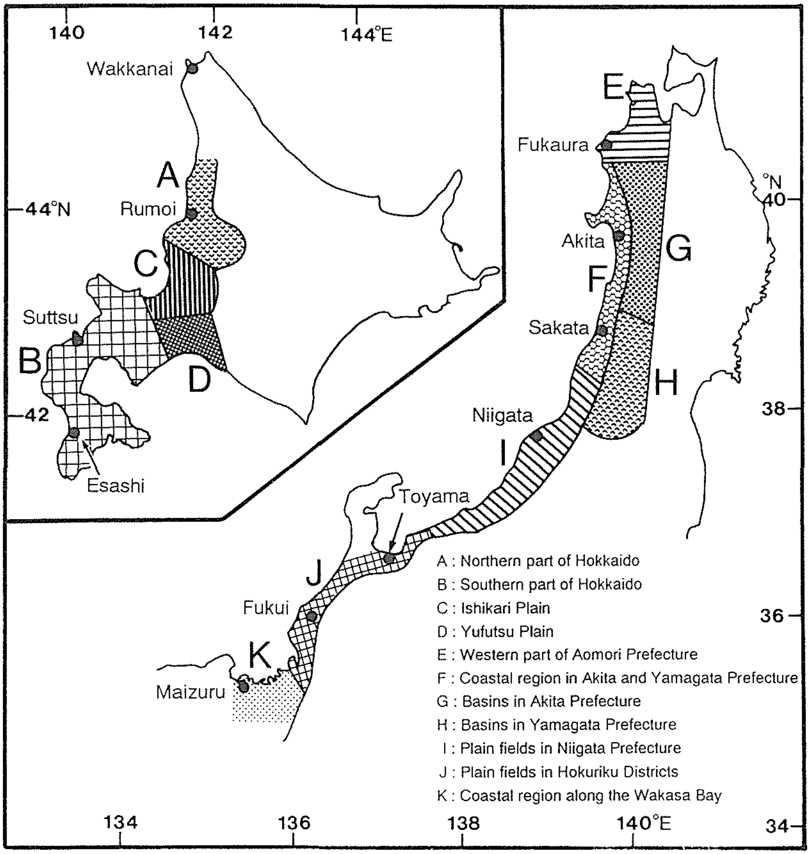

Fig. 4 Regional division of snow-depositional environments in plain areas along the Japan Sea coast determined by significant shifts in snow characteristics observed in 1986 and 1988. Solid circles represent the weather stations for which the snow metamorphism diagram was applied in Fig. 7.

RELATIONSHIPS BETWEEN SNOW METAMORPHISM AND METEOROLOGICAL CONDITIONS

One of the main objectives of this study was to develop a snow metamorphism diagram from which the relationships between meteorological parameters and the predominant type of metamorphism can be determined.

Akitaya & Endo (1977) found that the growth of depth hoar including both skeleton-type and solid-type was predominant when the mean temperature gradient was greater than 0.13°C cm^{-1}; on the other hand, fine-grained compact snow was in the majority when the gradient was less than 0.12°C cm^{-1}. The mean temperature gradient was obtained by dividing the mean air temperature in January by the mean snow depth in January. To generalize the above index for the snow cover season, a "temperature-gradient index" (*TG*-index) was introduced as an index for indicating the degree of temperature-gradient metamorphism (equation (1)):

$$TG\text{-index} = |T_a/H_s| \quad (1)$$

where T_a is the mean air temperature from the beginning of snow deposition to the day when the index is calculated, provided that *TG*-index = 0 when $T_a > 0$; H_s is the mean snow depth during the above period.

Contrary to the cases of depth hoar and fine-grained snow, the formation of coarse-grained granular snow is believed to depend mainly on the amount of water input within snow cover. The deeper the snow cover, the greater the amount of water necessary to ensure the metamorphism of the entire pack into coarse-grained granular snow. A "melt-freeze index" (*MF*-index) was introduced as an index for indicating the degree of melt-freeze metamorphism (equation (2)):

$$MF\text{-index} = (\sum T_{a+})/H_s \quad (2)$$

where ΣT_{a+} is the cumulative daily mean air temperature above 0°C during the above period.

Both indexes were calculated from the meteorological data at the nearest weather station (Japan Meteorological Agency) to the observation sites in 1986 and 1988. Relationships between both indexes and the predominant snow type at each observation site in 1986 and 1988 are shown in Fig. 5. The predominant snow type was largely classified into three: the depth hoar including both the skeleton-type and solid-type, the fine-grained compact snow and the coarse-grained granular snow, and was determined on the basis of the cumulative layer thickness of each snow type. Although the plots are somewhat scattered, the diagram can be divided into three parts according to the difference in snow type, as shown by the broken lines. The depth hoar predominates when the *TG*-index > 0.09°C cm^{-1}, not depending on the *MF*-index, while the fine-grained compact snow and coarse-grained granular snow predominate when the *TG*-index < 0.09°C cm^{-1}. Furthermore, the *TG*-index required for the predominance of fine-grained compact snow has a tendency to increase as the *MF*-index increases, although the boundary line between fine-grained compact snow and coarse-grained granular snow is somewhat uncertain because of insufficient data.

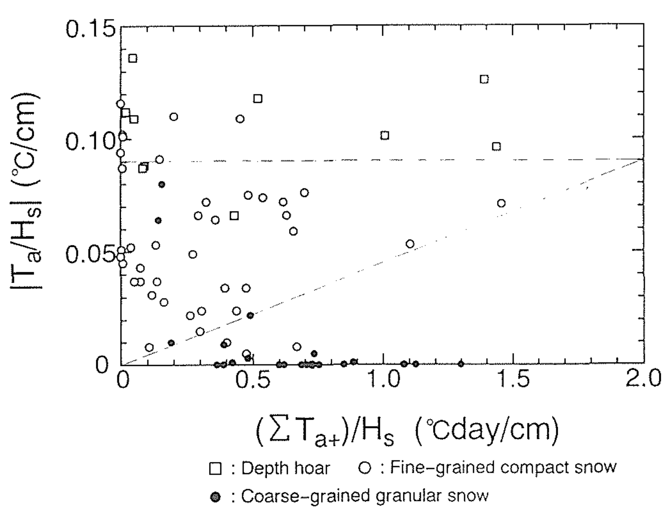

Fig. 5 Relationships between the *MF*-index, *TG*-index and predominant snow type at each observation site in 1986 and 1988.

The adequacy of the boundary lines, however, is supported by the application of independent data to this diagram. Figure 6 shows variations in both indexes at Sapporo in the winters of 1980/81-1982/83, together with the predominant snow type observed by Endo *et al.* (1981) and Endo & Akitaya (1982, 1983). Variations in snow type are in good accord with the three parts divided by the boundary lines, showing that this diagram is useful for estimating predominant snow types from the meteorological data. Since the snow type is determined by the type of metamorphism, this diagram can be taken as a snow metamorphism diagram showing the relationships between meteorological parameters and the predominant type of snow metamorphism.

REGIONAL CHARACTERISTICS OF SNOW METAMORPHISM

In order to identify the predominant type of snow metamorphism in plain areas along the Japan Sea coast, the snow metamorphism diagram was applied for 11 sites with latitude ranging from 35 to 45°N in the winters of 1975/76-1984/85 (10 winter seasons). The meteorological data used were obtained at weather stations of the Japan Meteorological Agency.

Figure 7 shows the frequencies of predominant metamorphism types at the end of February, when marked differences in snow characteristics are found from region to region. The melt-freeze metamorphism is the only type that predominates in the areas with latitude lower than 39°N. On the contrary, the melt-freeze metamorphism never predominates at the end of February and the temperature-gradient metamorphism has the highest frequency in the areas with latitude higher than 43°N. All types of metamorphism appear in the areas with latitude ranging from 39 to 43°N, suggesting that marked variations in snow characteristics occur from year to year.

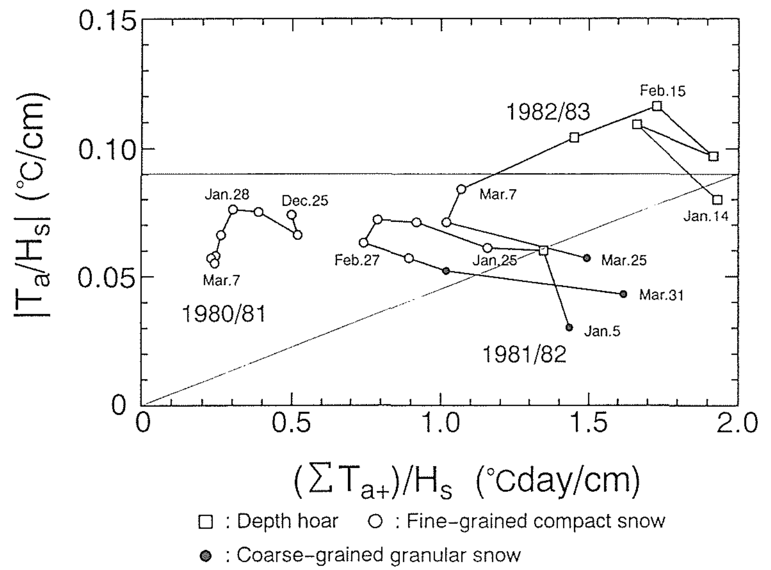

Fig. 6 Variations in the *MF*-index and *TG*-index at Sapporo in the winters of 1980/81-1982/83, together with those in predominant snow type.

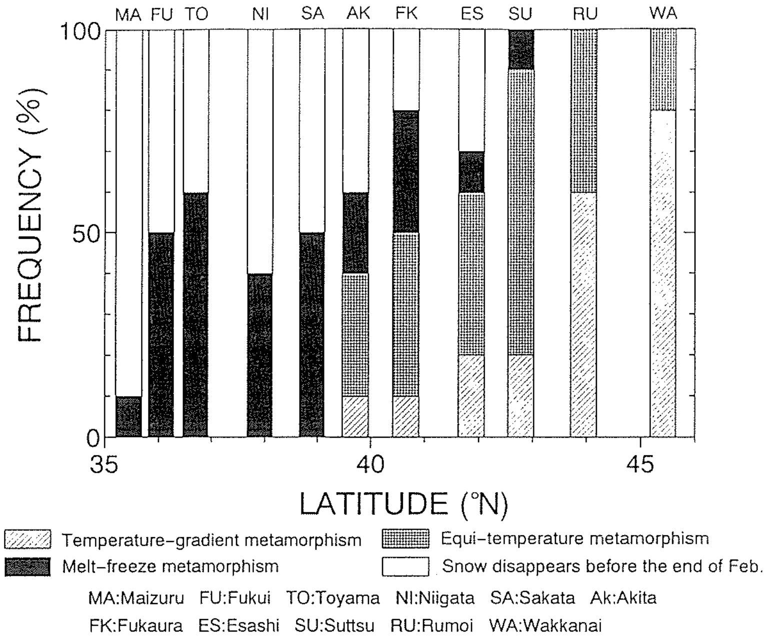

Fig. 7 Frequencies of predominant metamorphism types at the end of February in the winters of 1975/76-1984/85 at 11 weather stations shown in Fig. 4.

The mean values of T_a and H_s at the end of February for the 10 winter seasons (1975/76-1984/85) at the above sites except for Maizuru are shown in Fig. 8. An almost linear decrease in mean air temperature against latitude is seen. Since the mean air temperature in the areas with latitude lower than 39°N is above 0°C, melting occurs

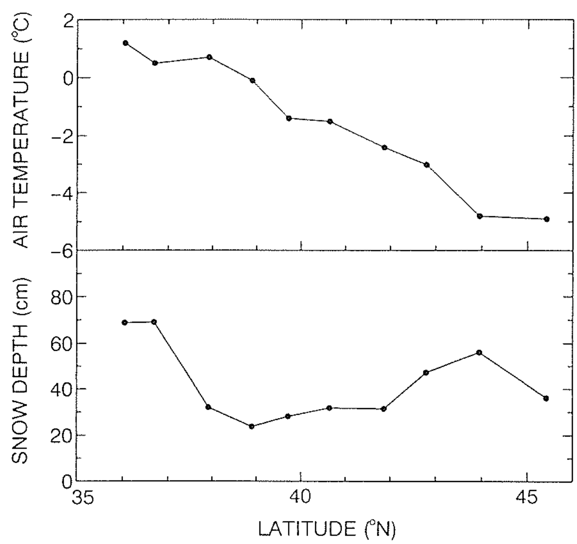

Fig. 8 Mean values of T_a and H_s at the end of February for 10 winter seasons (1975/76-1984/85) against latitude.

during the almost the whole period of the winter season in this area and results in the predominance of melt-freeze metamorphism. On the other hand, little or no melting may occur in the areas with latitude higher than 43° because the mean air temperature there is below −4°C. The reason why all types of metamorphism appear at latitudes 39-43°N is believed to be partly that the snow cover is subjected to air temperatures around or just below 0°C, and partly that the snow cover is comparatively thin. The climatic conditions make possible both the predominance of melt-freeze metamorphism in case of a slight rise in air temperature and that of temperature-gradient metamorphism in case of a slight drop in air temperature. In other words, the characteristics of snow cover at latitudes 39-43°N are highly sensitive to climatic and environmental changes.

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