Compactive Viscosity of Snow and Its Climatic Implications at Mizuho Station, Antarctica*

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雪の圧縮粘性とその気候学的意味*

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要旨 日本南極地域観測隊が得た，みずほ基地の雪の密度のデータ数は，第11次，第12次および第13次のものを合計すると3635にのぼる．これらの測定結果を吟味，整理したものを使って「圧縮粘性係数」の深さ分布が求められた．みずほ基地の雪に限らず，一般に極地の雪の圧縮粘性係数は，季節的積雪，たとえば北海道の雪に比べて約100倍大きい．これは，極地における長期間の圧密過程において，氷粒子間の結合が極度に成長したためと解釈される

みずほ基地の雪において，密度の測定値は，深さ約30 m～40 mの領域で，大きく振動し，かつ平均的傾向曲線からはずれた．圧縮粘性係数は，この深さ領域で鋭い極大を示した これらの結果は，この層の雪が蓄積した時，年間蓄積量の少ない寒冷な時期が繰返しかつ持続して襲来したことを示唆する．その時期は，雪の年間蓄積量から約300年前と推定される．

***Abstract*:** The compactive viscosity coefficient of snow was obtained from a density profile at Mizuho Station, Antarctica The value of the compactive viscosity coefficient was by two orders of magnitude larger than that of ordinary seasonal snow The large value was attributed to strong bonds between constituent ice particles within Antarctic snow which had been aged for prolonged periods

A sharp peak of the compactive viscosity coefficient was found in a limited range of the depth around 35 m, that is in a range of the density around 750 kg m^{-3} In the depth range from 30 m to 40 m the layer-to-layer densities varied largely and the mean density deviated markedly from a smoothed general trend These results suggest that a colder climate occurred repeatedly and lasted approximately 300 years before the present in the vicinity of Mizuho Station

1. Introduction

The process of densification of snow is one of the most important and interesting problems in glaciology and snow-engineering. Fresh snow crystals, after deposited on

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the surface, are subjected to the modification of their shapes and physical properties through various sintering processes. They make bonds with each other and at the same time individual crystal grains grow larger. In glaciers and ice sheets the snow subsides steadily and its bulk density increases under the pressure of overlying snow. The snow density reflects totally the climatic circumstances of the region where the snow has been accumulated and aged.

BADER (1960, 1963) obtained empirical relations between the snow density and the depth from the surface, which have been usefully applied to engineering problems of foundation settlement and tunnel closure in Greenland and Antarctica. The density-depth relation of snow was also studied by BENSON (1962), ANDERSON and BENSON (1963), COSTES (1963), KOJIMA (1964), LANGWAY (1967) and GOW (1968) using the data obtained from core samples drilled at various polar sites. However, detailed characteristics of density-depth relations and especially effects of climatic changes have not been investigated.

In the ice-coring project (1970–1975) of the Japanese Antarctic Research Expedition (JARE), three separate series of core samples were recovered safely at Mizuho Station (70°41′53″S, 44°19′54″E; 2230 m above the sea level; ice thickness 2095 m; mean annual temperature −33°C) in East Antarctica (SUZUKI and TAKIZAWA, 1978). Among them densities of the two series of cores were measured in detail and numerical data obtained were examined and compiled by NARITA and MAENO (1978). The present paper aims to analyze the numerical density data with a special reference to the viscous compaction of snow and to the effect of climatic changes on the densification process.

2. Density and Physical Characteristics of Snow at Mizuho Station

Individual snow densities measured at 1533 different points between the surface and the depth of 60 m are shown in Fig. 1. The diagram was represented to show that the fluctuation of the density is considerably large as compared with that in other glaciers. According to GOW's (1968) measurements at Byrd Station, snow densities varied from layer to layer by about 100 $kg \cdot m^{-3}$ near the surface but the variations tendend to dampen rapidly with increasing depth, namely 30 $kg \cdot m^{-3}$ at 3 or 4 m and about 15 $kg \cdot m^{-3}$ at 10 m, and at 20 m they rarely exceeded 10 $kg \cdot m^{-3}$. It is clear in Fig. 1 that the variations of snow density at Mizuho Station are much larger; layer to layer densities near the surface vary by as much as 200 $kg \cdot m^{-3}$. These variations decrease with depth: roughly 100 $kg \cdot m^{-3}$ at 5 m, 40 $kg \cdot m^{-3}$ at 10 m, 30 $kg \cdot m^{-3}$ at 20 m and 20 $kg \cdot m^{-3}$ at 30 m. The large amplitude of variations is considered to be related to the characteristic snow accumulation at Mizuho Station, which will be mentioned later.

It should also be noted in Fig. 1 that the variations of snow densities increase again

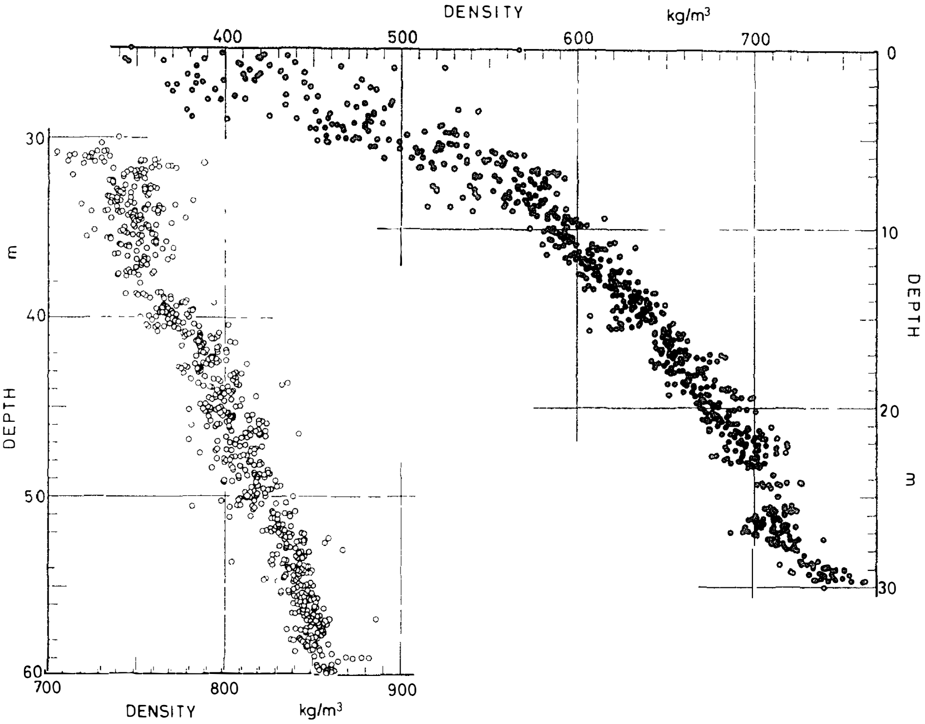

Fig. 1. Individual snow densities measured at Mizuho Station. Numerical data are after NARITA and MAENO (1978).

to some 60 kg·m^{-3} at depths between 30 m and 35 m. Below the depth of 40 m the variations do not change essentially and maintain an almost constant value around 30 kg·m^{-3}, though the value is much larger as compared with other glaciers.

Fig. 2 shows the mean density plotted against the depth, together with the cumulative mass of overlying snow. Each value of the density is a mean of some 15 measurements at different points within a 0.5 m depth, which are shown in Fig. 1. The overall density-depth curve can be divided into four regions by breaks of slope at depths of approximately 8 m, 30 m and 55 m, which are indicated by marks A, B and C in the figure. The corresponding densities are 550 kg·m^{-3}, 730 kg·m^{-3}, and 840 kg·m^{-3}, respectively.

The two critical densities, 550 kg·m^{-3} (A) and 840 kg·m^{-3} (C), have often been noted in other glaciers and explained as follows: snow deposits in cold regions undergo a densification process firstly of mechanical destruction and packing of ice particles till a critical density of 550 kg·m^{-3}, secondly of compaction by plastic deformation and recrystallization till 840 kg·m^{-3}, and finally of the shrinkage of entrapped bubbles until the density of solid ice (917 kg·m^{-3}) is attained (PERUTZ and SELIGMAN, 1939; BENSON, 1962; ANDERSON and BENSON, 1963; LANGWAY, 1967).

In regard to the first critical density of 550 kg·m^{-3}, ANDERSON and BENSON (1963)

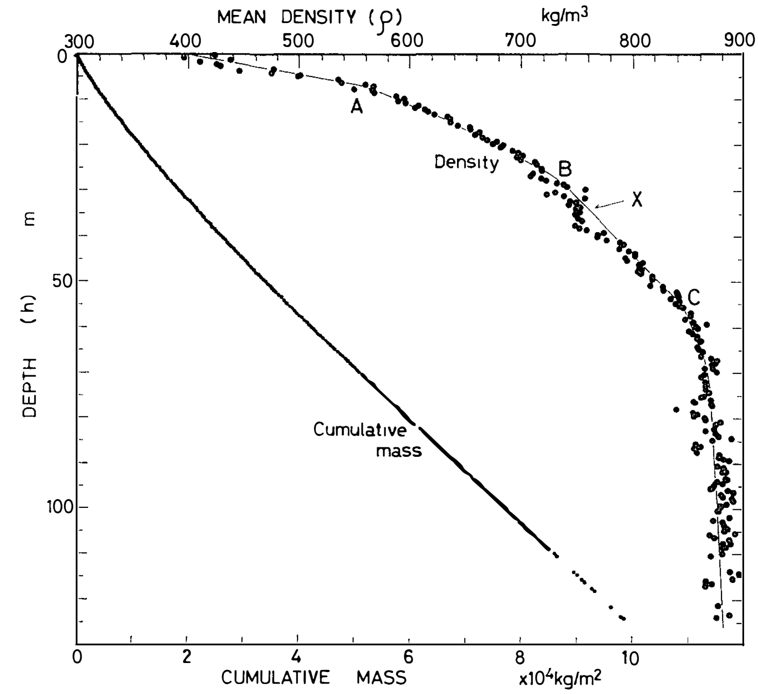

Fig 2 Mean density and cumulative mass of overburden snow per unit area. Each value of the density is a mean in a 0 5 m interval of depth

gave an explanation that it corresponds to the maximum packing density that can be attained with granular aggregates. From examinations of thin sections of snow at Byrd Station, however, Gow (1968) claimed that he could find little evidence for the formation of a simply mechanically packed structure at the critical density, and has suggested that the overall bonding between ice particles is already strong enough to prevent any widespread collapse of the snow structure. But taking into account the change of electric and permeability properties and the increase in the specific area of grain boundary at the critical density (MAENO *et al.*, 1978; NARITA *et al.*, 1978), the explanation by ANDERSON and BENSON seems reasonable.

The value of the other critical density marked as **B** in Fig. 2 is 730 $kg \cdot m^{-3}$, and its depth is about 30 m. On the basis of electrical measurements, MAENO (1974 a, 1974 b, 1978) explained as follows: at the critical density the bonding and packing mode of constituent ice particles reaches an optimum state, that is the contact between particles is maximum and air voids are included only at intersections of several grain boundaries. This explanation has been supported by other measurements of petrofabric structures (NARITA *et al.*, 1978) and elastic modulus and air permeability (MAENO *et al.*, 1978).

In the density-depth curve in Fig. 2, a significant fluctuation and deviation of data from a smoothed trend are noted in a depth range from 30 m to 40 m, which is marked **X** in the figure: the density variations are found in a range from 30 m to 33 m and deviations in a range from 32 m to 40 m. The depth region marked X corresponds to that in which variations of individual measured densities increased again in Fig. 1. These results suggest that some drastic change in a climatic condition has occurred in the past in the vicinity of Mizuho Station, which will be discussed later in more detail

3. Snow Accumulation at Mizuho Station

In still conditions snow is deposited uniformly, which produces regular horizontal layers However, at Mizuho Station where the strong katabatic wind blows almost all through the year, the mode of deposition is quite different and the process of snow accumulation is remarkably complicated; the deposition and erosion of snow are irregular in space and time, creating various complex surface relief such as dunes, sastrugi, and so on. Thus the snow accumulation at Mizuho Station is sporadic and local absence of annual layers is sometimes observed (WATANABE, 1978).

Although many trials have been made to estimate the net accumulation rate of snow at Mizuho Station, its reliable figure has not yet been obtained. On the basis of the measurements by JARE-12 and JARE-13 of snow accumulation by means of stakes set on the snow surface (YAMADA *et al*, 1975), INOUE *et al* (1978) estimated an average net accumulation rate of snow at Mizuho Station to be $A=45$ kg m^{-2} a^{-1}. On the other hand, using the same numerical data YAMADA and WATANABE (1978) gave $A=43$ kg·m^{-2} a^{-1} for the year 1972 and $A=18$ kg·m^{-2} a^{-1} for 1973 with standard deviations of 54 kg·m^{-2} a^{-1} and 41 kg·m^{-2} a^{-1} respectively. Furthermore, YAMADA and WATANABE obtained even different values in the same region and period when they used different numbers of stakes set in different configurations: $A=18$ kg·m^{-2} a^{-1} and 48 kg·m^{-2} a^{-1} in 1973 for 36 and 200 stakes respectively, and $A=0$ kg·m^{-2} a^{-1} and 7 kg·m^{-2} a^{-1} in 1974 for 36 and 200 stakes respectively. The variability of the results is apparently caused by the appreciably complicated process of snow accumulation at Mizuho Station, which indicates the difficulty of estimating the average net accumulation rate of snow.

On the other hand, we have evidence to the steady accumulation of snow at Mizuho Station in view of a relatively longer time scale According to structural analyses of the Mizuho cores the rate of snow accumulation seems to be much larger; though the stable oxygen isotope method for detecting annual layers was not successful, WATANABE *et al.* (1978) obtained a value of $A=106$ kg·m^{-2} a^{-1} from visual determinations of annual layers in the core samples, and NARITA and MAENO (1979) gave a figure of roughly 70 kg·m^{-2} a^{-1} based on the measurement of the growth rate of crystal grains in the core samples. These values should be considered to be the mean in a relatively longer term, say a few hundred years.

Another possibility of estimating the mean net accumulation rate of snow can be

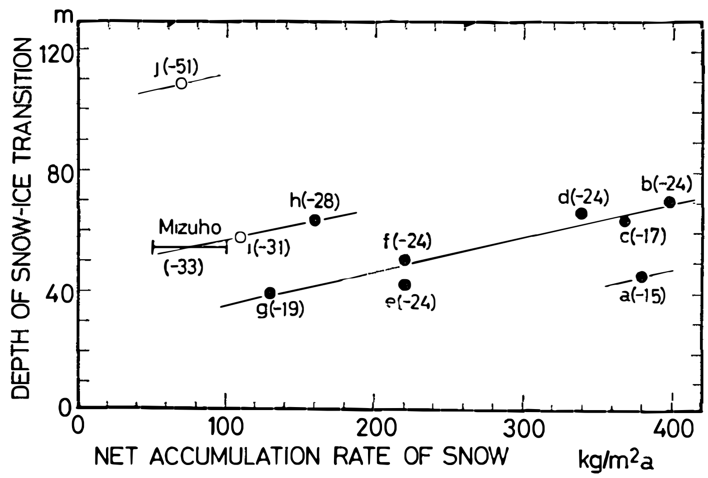

Fig 3. Depth of snow-ice transition versus the net accumulation rate of snow Open circles indicate depths of 830 kg m^{-3} estimated by extrapolation in density-depth curves. Numbers in parentheses denote the mean annual temperature (°C), and letters refer to locations: a (Roi Baudouin), b (Site 2), c (Maudheim), d (Camp Century), e (Ellsworth), f (Little America V), g (Wilkes S–2), h (Byrd), i (Southice) and j (South Pole). Literatures used are cited in GOW *(1968).*

given from density measurements or structure analyses of snow, since the depth at which snow transforms into ice in subsiding is determined mainly by the net accumulation rate and the temperature.

Depths of snow-ice transition, *i. e.* depths at which the air permeability becomes zero (about 820–840 $kg \cdot m^{-3}$ in density), found at various locations in Antarctica and Greenland, are plotted in Fig. 3 as functions of the net accumulation rate of snow and the mean air temperature. Open circles indicate depths of 830 $kg \cdot m^{-3}$ found by extrapolation in density-depth curves.

The number of data is not large, but it may be clear that a close relation can be found between the depth of snow-ice transition and the other two factors: the larger the net accumulation rate of snow and/or the lower the mean annual temperature, the smaller the density increase over a given increment of depth, and therefore the deeper the depth at which snow transforms into ice. The rough extrapolation suggests that the net accumulation rate of snow at Mizuho Station lies between 50 and 100 $kg \cdot m^{-2} a^{-1}$, which is in reasonable agreement with the results of the stake-measurements and core analyses.

4. Compactive Viscosity of Snow at Mizuho Station

In analyses of the natural densification of snow layers YOSIDA *et al.* (1956) and BADER (1960) assumed a linear relationship between the strain rate and the load applied, and defined a "compactive viscosity coefficient", η, as

$$\dot{\varepsilon}=-\eta\sigma \tag{1}$$

where $\dot{\varepsilon}$ and σ are the strain rate and the compressive pressure respectively. η is positive since $\dot{\varepsilon}$ is always negative in the compressive deformation The physical meaning of η is not necessarily the same as that of the viscosity coefficient frequently used in the theories of elasticity and rheology since the viscous compression of snow always accompanies the alteration of the geometrical and mechanical structure.

The strain rate, $\dot{\varepsilon}$, of an arbitrary snow layer of a thickness, h, and density, ρ, is represented as

$$\dot{\varepsilon}=\frac{1}{h}\frac{dh}{dt}=-\frac{1}{\rho}\frac{d\rho}{dt}, \tag{2}$$

provided that the mass of the snow layer is conserved, that is ρh=constant. The increment of the compressive pressure within a small time interval, dt, is $d\rho=Agdt$, where A is the rate of snow accumulation and g is the acceleration of gravity. Then eq. (2) is written as

$$\dot{\varepsilon}=-\frac{Ag}{\rho}\frac{d\rho}{d\sigma}. \tag{3}$$

This is actually one of the conclusions of the Sorge's law stating that, when a glacier is stationary, *i. e.* the climate including the rate of snow accumulation and temperature does not change, the function $\rho=f(h)$ is invariant with time (BADER, 1953)

Combining eqs. (1) and (3) we get

$$Ag\eta\frac{d\rho}{\rho}=\sigma d\sigma . \tag{4}$$

Integrating eq. (4) in a small region ($\rho_1\sim\rho_2$, $\sigma_1\sim\sigma_2$) in which A and η can be assumed to be constant, we obtain

$$Ag\eta \ln\frac{\rho_2}{\rho_1}=\frac{1}{2}(\sigma_2^2-\sigma_1^2) . \tag{5}$$

This relation suggests that the compactive viscosity coefficient can be estimated from a slope of a density-pressure curve.

Fig 4 gives an example of the plot of $\ln\rho$ against $\sigma^2/2$ in a density range near 750 kg·m^{-3}. Drawing a reasonable line to fit observed data, we can get numerical values of $Ag\eta$ from its slope. Then we can estimate η at each density or depth if A and g are known. But it should be noted that this method of estimating η is not absolutely accurate because of uncertainty involved in the line fitting.

The compactive viscosity coefficient of snow at Mizuho Station calculated from a

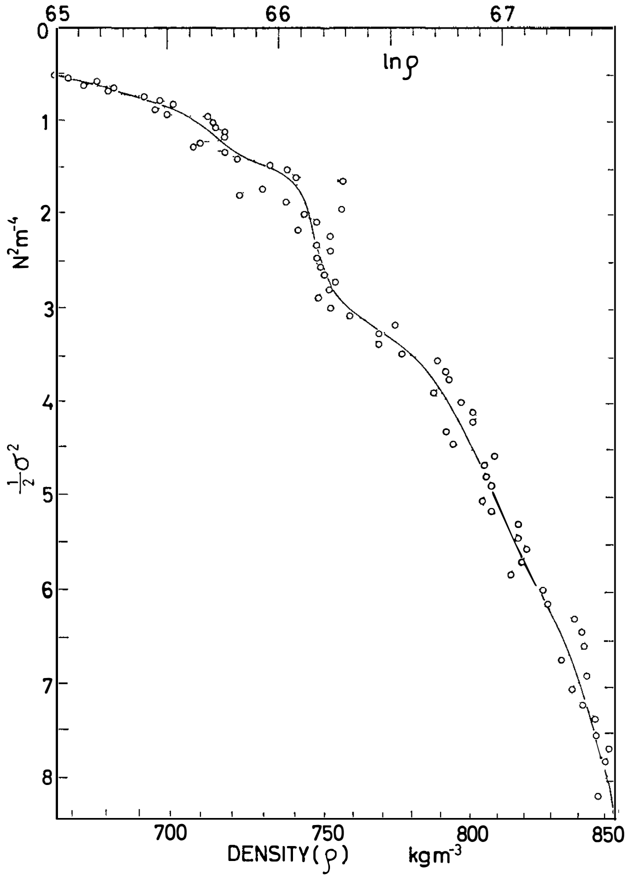

Fig 4 Plot of ln ρ *against* $\sigma^2/2$ *in a density range near 750 kg m*$^{-3}$ *(Mizuho Station)*

smoothed line as shown in Fig. 4 is given in Fig. 5. In the calculation values of A and g were put 50 kg·m^{-2} a^{-1} and 9.82 m·s^{-2} (Abe, 1975) respectively, and η was estimated in each interval of ln ρ of 0.005. The value of η when A was put to be 100 kg·m^{-2} a^{-1} is also represented by a dashed line.

The general trend of η is the increase with increasing density, and accordingly the absolute value of strain rate becomes smaller with increasing density. This corresponds to the decrease in the densification rate and the increase in the slope of the density curve with increasing depth (Fig. 2). The strain rate was roughly -2.1×10^{-10} s^{-1} (-6.5×10^{-3} a^{-1}) at 500 kg·m^{-3}, -4.8×10^{-11} s^{-1} (-1.5×10^{-3}a^{-1}) at 600 kg·m^{-3}, -2.0×10^{-11} s^{-1} (-6.2×10^{-4} a^{-1}) at 700 kg·m^{-3} and -1.2×10^{-11} s^{-1} (-3.7×10^{-4} a^{-1}) at 800 kg·m^{-3}. Accordingly the density interval of Δ(ln ρ)=0.005 in the calculation corresponds to approximately 0.8 a at 500 kg·m^{-3}, 3 3 a at 600 kg·m^{-3}, 8.1 a at 700 kg·m^{-3} and 13.7 a at 800 kg·m^{-3}. These figures are fairly large and indicate that this method of estimating η can give information in the densification process of snow at extremely slow rates that are almost impossible to attain in laboratories.

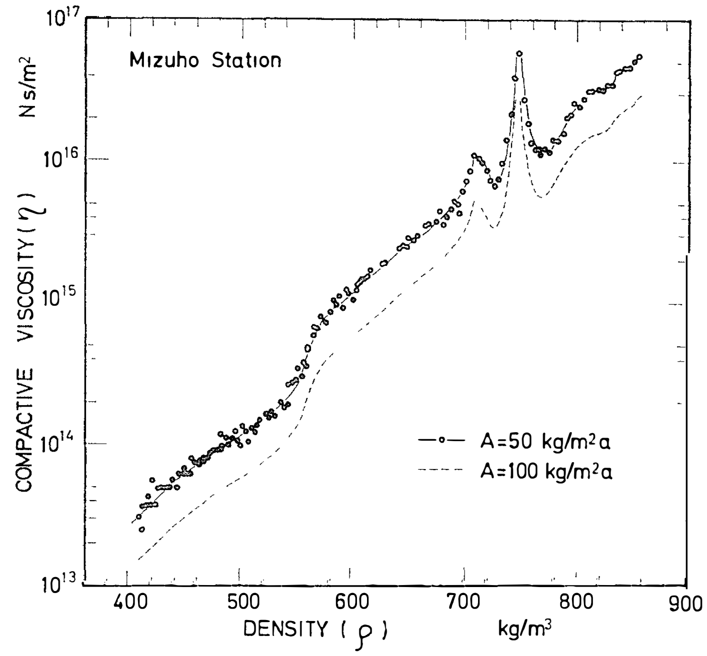

Fig. 5. Compactive viscosity coefficient plotted against the density (Mizuho Station, $A=50$ kg m^{-2} a^{-1}). The dashed line indicates the compactive viscosity when A is 100 kg m^{-2} a^{-1}.

In Fig. 5 the rather rapid increase in η near the density of 550 $kg \cdot m^{-3}$ is considered to be associated with the alteration of the densification mechanism mentioned earlier.

A sharp peak of η near the density of 750 $kg \cdot m^{-3}$ is caused by the deviation of the density from the general trend, marked X in Fig. 2. The extremely large value of η implies that the snow in the density range is mechanically very strong and suggests that the snow has experienced some climate in which the mechanical strength of snow is greatly increased. The precise process of strength-increasing is not clear, but one possibility may be the repeated occurrence and duration of a relatively colder climate. In a cold climate the rate of snow accumulation is expected to be small, hence the time for the particular snow layer to remain near the surface may be long. This situation can make the snow layer to be strengthened possibly by two causes; one is the long exposure to winds and solar radiation, and the other is the prolonged establishment of relatively strong temperature gradients within the snow layer to result in the upward transfer of water vapor and the growth of strong solid-type depth hoars (AKITAYA, 1974).

The repeated occurrence of a cold climate or extremely small-accumulation period is suggested by the large variations of densities around the density of 750 $kg \cdot m^{-3}$ or the depth of 35 m (Figs. 1 and 2), and its prolonged duration is suggested by the deviation of densities from the general trend (X in Fig. 2) and the peak of the compactive viscosity coefficient (Fig. 5). The occurrence of a cold climate is also manifested by the marked negative peak of $\delta^{18}O$ values found at the depth of 32 m in Mizuho core samples (WATANABE *et al.*, 1978).

From the analysis of the snow accumulation rate, the time of occurrence of the cold climate is roughly estimated to be 300 years before the present. It is also important to take into account the effect of flow of the ice sheet. According to NARUSE's (1978) estimation based on his triangle-chain surveys on the Mizuho Plateau, the horizontal surface velocity of flow at Mizuho Station is roughly 15 $m \cdot a^{-1}$. If the flow velocity is assumed not to vary in a surface layer of a few ten meters, the snow at the depth of 35 m is estimated to have been accumulated at a point approximately 50 km upstream from Mizuho Station. Consequently, the compactive viscosity coefficients

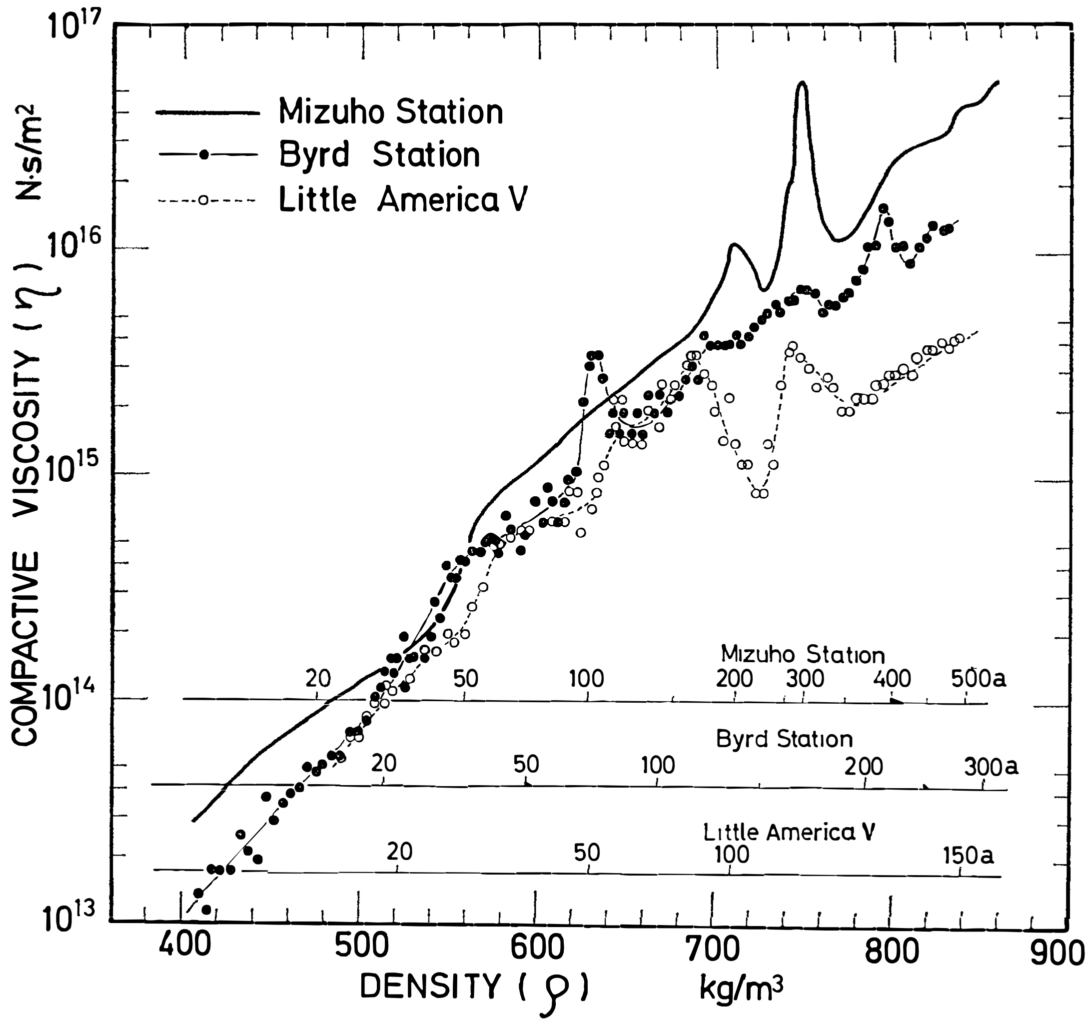

Fig 6 Compactive viscosity coefficient of snow at Byrd Station and Little America V The solid line refers to Mizuho Station ($A=50$ kg m^{-2} a^{-1}) Time scales were calculated from the cumulative mass of overburden snow by assuming that snow accumulation rates were $A=75$ kg m^{-2} a^{-1} at Mizuho Station, $A=160$ kg m^{-2} a^{-1} at Byrd Station and $A=220$ kg m^{-2} a^{-1} at Little America V.

and their implications deduced above should be considered to be applicable not to the narrow area at Mizuho Station but to a region in the vicinity of Mizuho Station with space comparable to the appropriate flow distance.

Fig. 6 shows the compactive viscosity of snow at other locations in Antarctica, namely Byrd Station (mean annual temperature $\theta=-28°C$, net accumulation rate of snow $A=160\ kg\cdot m^{-2}\ a^{-1}$) in west Antarctica and Little America V ($\theta=-24°C$, $A=220\ kg\cdot m^{-2}\ a^{-1}$) on the Ross Ice Shelf. Values of η were calculated with the same method given above using the numerical data of densities measured by GOW (1968)

The general relation between the compactive viscosity and the density is similar to that at Mizuho Station, namely the compactive viscosity increases with increasing density. But its values are appreciably different at three points especially in a density range above $700\ kg\cdot m^{-3}$. The difference can be attributed to that in the mean annual temperature and the time of aging As shown in the time scales given in Fig. 6, the aging time of snow at Mizuho Station is considerably longer than that at other points, and consequently the bonds between constituent ice particles are considered to have developed more strongly to result in the increase in the compactive viscosity

5. Concluding Remarks

The compactive viscosity coefficient of snow gives more information about the physical nature of snow and past changes in the climatic circumstances where the snow has been accumulated and aged, since the physical meaning of the compactive viscosity is more clearly defined than density-depth relations themselves. In respect to the compactive viscosity of snow at Mizuho Station, some colder climate was suggested to have occurred repeatedly and lasted some 300 years before the present in the vicinity of Mizuho Station. It might be interesting to discuss the possibility whether such cold climate occurred only locally around Mizuho Station or more widely in other regions in Antarctica, and whether the cold climate found in the vicinity of Mizuho Station took place globally on the earth and corresponds to the so-called "Little Ice Age (1600–1730)" known to have occurred in the northern hemisphere, which was directly confirmed with analyses by JOHNSEN *et al* (1970) However, there are no reliable evidences available now to verify these possibilities. To obtain any definite conclusions, it seems quite necessary to drill cores down to a depth of several tens of meters at as many points as possible in Antarctica and to analyze the core samples in a similar way to that presented in this paper.

Finally, values of compactive viscosity of snow in Antarctica are compared with those of seasonal snow in Fig 7. Values of compactive viscosity of snow in Antarctica are by two orders of magnitude larger than those of seasonal snow in Hokkaido, Japan

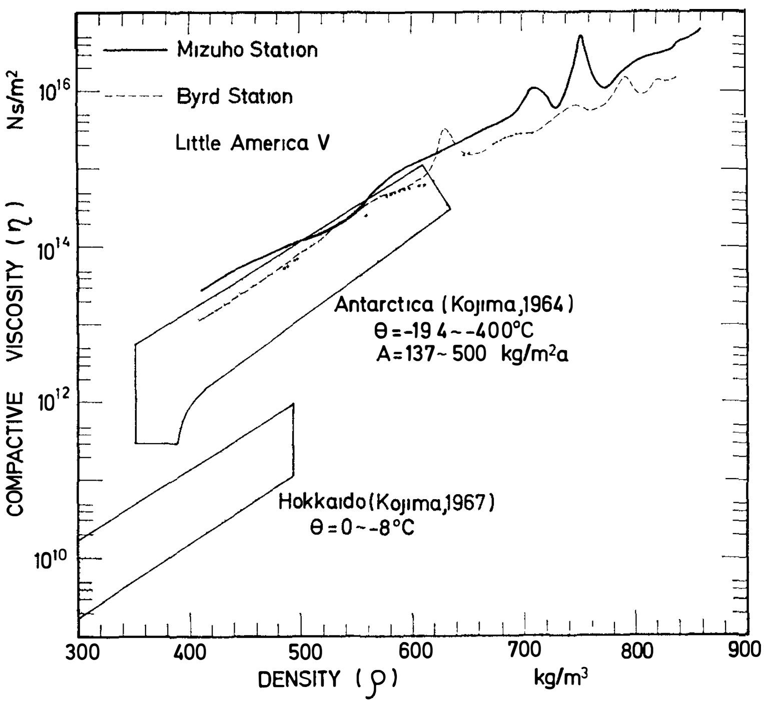

Fig. 7. Compactive viscosity coefficients of snow at various locations. The values for Mizuho Station are the case when $A=50$ kg $m^{-2}a^{-1}$.

(KOJIMA, 1967). The main cause of this difference is considered to be the bond growth between ice particles during the prologed aging period in Antarctica.

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