INITIAL STAGE OF DENSIFICATION OF SNOW IN MIZUHO PLATEAU, ANTARCTICA

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***Abstract*:** The initial stage of densification of snow was investigated for four 30-m snow cores drilled in Mizuho Plateau, Antarctica, with special reference to the critical density of 550 kg/m^3, and to compactive viscosity. The density-depth relations were considerably different among the four cores, but the depth of the density 550 kg/m^3 was noted to increase with the distance from the coast. The result could be explained by a physical dependence of snow densification on temperature and accumulation rate.

The compactive viscosity coefficient, η, calculated from the density-pressure curves was expressed by an equation $\eta=\eta_0 \exp(b\rho) \exp(E/kT)$, where k and T are respectively Boltzmann's constant and temperature, and $\eta_0=1.20\times10^{-8}$ N$\cdot$s/m^2, $b=2.57\times10^{-2}$ m^3/kg and $E=51.6$ kJ/mol. A densification model was constructed to estimate the pressure or depth at which the critical density 550 kg/m^3 is reached, as a function of temperature and accumulation rate. The model in turn makes it possible to estimate the annual accumulation rate at any observation site from the depth at which the density reaches 550 kg/m^3 and the mean annual temperature given by the 10-m depth temperature.

1. Introduction

The densification of snow is one of the most important and fundamental problems in polar glaciology. It has been described variously as diagenesis (BENSON, 1962; ANDERSON and BENSON, 1963) and sintering (GOW, 1969; MAENO, 1982). The initial stage of densification, until the critical density of 550 kg/m^3 is reached, has been attributed to the mechanical packing and destruction of ice particles, although its detailed characteristics have scarcely been studied.

The densification rate in this initial stage depends upon several parameters, including temperature, accumulation rate, wind speed and temperature gradient in snow, of which temperature and accumulation rate are considered the most important. In the present study, measurements of densities were made in the top 30 m of snow at four stations on the Mizuho Plateau, East Antarctica, to evaluate the effect of temperature and accumulation rate on the initial stage of densification.

2. Glaciological Conditions of Sampling Stations

Samples for density measurements were obtained from 30 m-long snow cores, drilled with an electric drill (mechanical) at four stations on the Mizuho Plateau. The four stations are shown in Fig. 1: S18 (69°02'S, 40°07'E), W'200 (69°35'S, 48° 50'E), U234 (71°01'S, 47°29'E) and V142 (72°32'S, 51°57'E). S18 (elevation: 600 m above sea level) is located about 25 km from the coast. The elevations of W'200 and U234 are 2000 m and 2640 m, respectively. V142 is located on an ice divide, 3076 m above sea level, between the drainage basins of Shirase Glacier and Lambert Glacier.

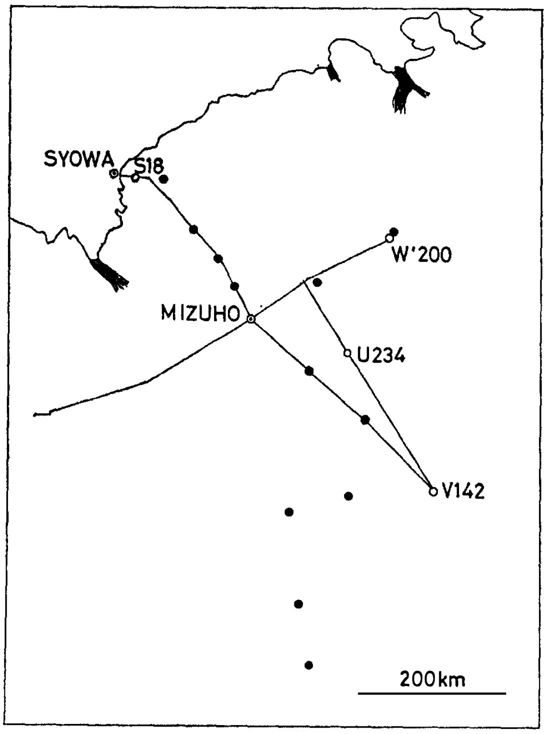

Fig. 1. Map of Mizuho Plateau showing locations of drilling stations. Open and closed circles indicate the stations where 30-m and 10-m core sampling was conducted, respectively.

According to WATANABE *et al.* (1981), the coastal region, to which S18 and W'200 belong, is characterized by high accumulation rates and continuous layer distribution. U234 is located in a katabatic slope region, characterized by large regional variations in the annual accumulation rate with some annual layers missing. V142 is in a high inland region, characterized by a low annual accumulation rate, with uniform and continuous layering.

Snow temperatures at 10 m depth are −15.9°C at S18, −33.1°C at W'200, −38.5°C at U234 and −48.1°C at V142; these are considered to be close to mean annual air temperatures at those sites. Mean annual accumulation rates were estimated from stratigraphic analyses of the cores, as 210 kg/m^3·a at S18, 290 kg/m^3·a at W'200, 190 kg/m^3·a at U234 and 90 kg/m^3·a at V142.

3. Density Profiles

Snow densities were measured at intervals of less than 0.1 m. Figure 2 shows the density-depth relations at the four stations. The variations of snow densities from layer to layer tend to decrease with increasing depth, though the magnitudes of the variations are different among the four profiles: The ranges at 3 m are 80 kg/m^3 at S18, 70 kg/m^3 at W'200, 100 kg/m^3 at U234 and 110 kg/m^3 at V142, respectively and those at 10 m are 39 kg/m^3 at S18, 42 kg/m^3 at W'200, 58 kg/m^3 at U234 and 65 kg/m^3 at V142, respectively.

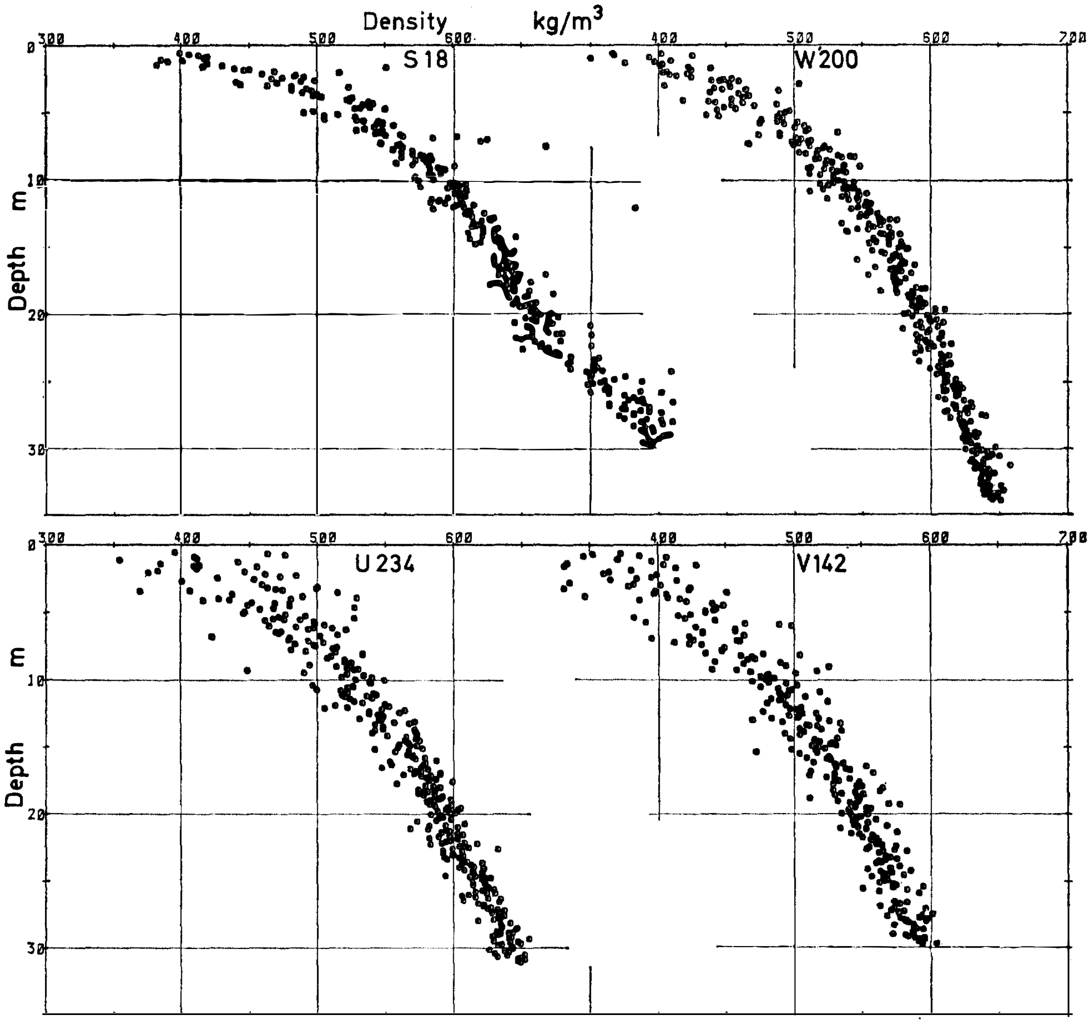

Fig. 2. Plot of individual snow densities against depth at stations S18, W'200, U234 and V142.

The variations at S18 are quite large, possibly because of melting in summer seasons. In this profile, a rapid increase in the density is noted below about 21 m, which is considered to be related with some change in ice flow or climate.

Gow (1968), Maeno and Narita (1979) and Alley (1980) reported similar variations of snow density for Byrd, Mizuho and Dome C cores, respectively. The magnitudes of the variations at the depth of 10 m at S18 and W'200 are similar to those at Mizuho (30 kg/m^3 at 10 m depth). The magnitudes at U234 and V142 are larger than those at Mizuho, but are similar to those at Dome C (60 kg/m^3 at 10 m depth). It seems that the magnitude of the density variations tends to increase in the inland area.

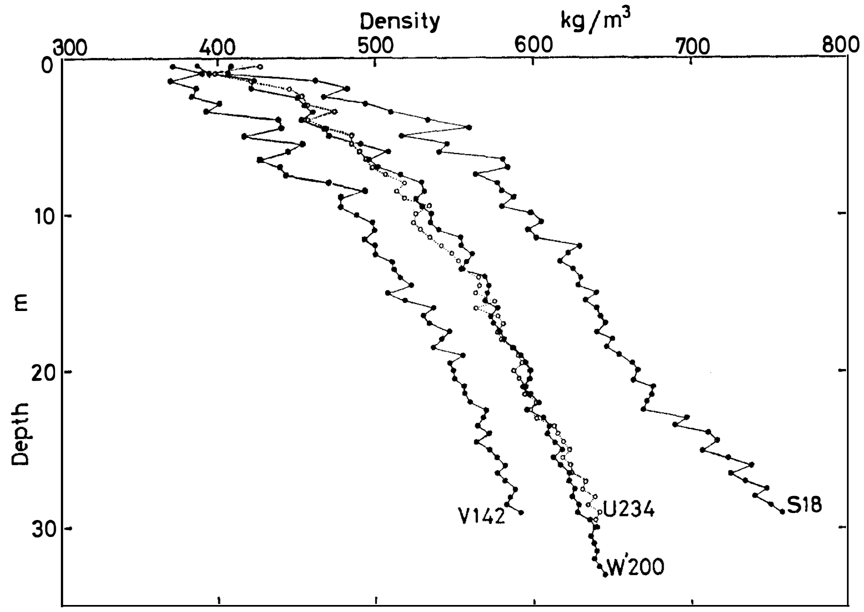

Fig. 3. Density-depth profiles at the stations S18, W'200, U234 and V142. Each value of density is a mean over a 0.5 m interval of depth.

Figure 3 shows density-depth relations at the four stations. Each value of the density is a mean over an interval of 0.5 m. Near the surface, the differences of snow densities among the four stations are small; this result is similar to that of YAMADA and WATANABE (1978). Densities at 0–1 m depth are 410 kg/m^3 at S18 and U234, 390 kg/m^3 at W'200 and 380 kg/m^3 at V142. It is clear from Fig. 3, however, that the density differences among the four stations tend to increase with depth: the densities at 20 m are 670 kg/m^3 at S18, 600 kg/m^3 at W'200, 590 kg/m^3 at U234 and 550 kg/m^3 at V142. The rate of density increase with depth is larger at S18 and smaller at V142 than at W'200 or U234. The density-depth profiles at W'200 and at U234 are similar.

4. Depth of the Critical Density 550 kg/m^3

The critical density of 550 kg/m^3 can be observed in Fig. 3 to be the point of change in slope of the density-depth curves. Depths of the critical density, 550 kg/m^3, are different at the four stations, being 6.0 m at S18, 11.5 m at W'200, 12.5 m at U234 and 20.0 m at V142. These are plotted in Fig. 4 against the distance from the coast. Data obtained from various 10-m snow cores on Mizuho Plateau (WATANABE, 1977) and from the 124-m core at Mizuho Station (NARITA and MAENO, 1978) are also plotted in Fig. 4: some depths were estimated by extrapolation of the density-depth curves, when they were deeper than 10 m. The increase in the depth at which the

550 kg/m^3 density occurs, with increasing distance from the coast seems to be associated with the variation of mean annual air temperature and accumulation rate, both of which decrease with increasing distance from the coast (SATOW, 1978; YAMADA and WAKAHAMA, 1981).

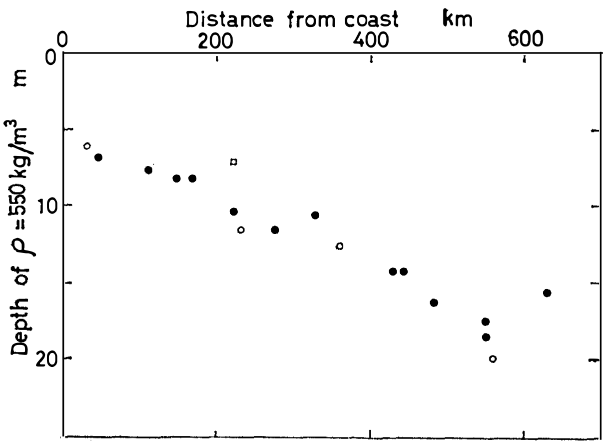

Fig. 4. Relation between the depth of the critical density 550 kg/m^3 and the distance from coast. Open circles indicate the plots for 30-m cores and closed circles for 10-m cores (WATANABE, 1977). The square represents the Mizuho Station cores (NARITA and MAENO, 1978).

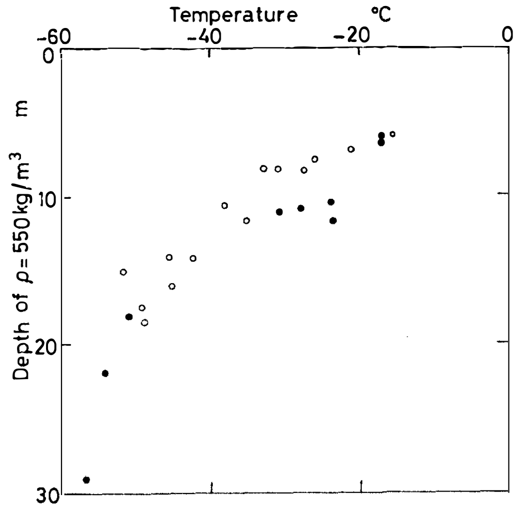

Fig. 5. Relation between mean annual temperature and the depth of density 550 kg/m^3. Open circles indicate the data from Mizuho Plateau and closed circles from other areas in Antarctica (ALLEY, 1980; GOW, 1968; BARKOV, 1973; HOINKES, 1962; STEPHENSON, 1967; TONGIORGI et al., 1962).

The relationship between the mean annual temperature and the depth of density 550 kg/m^3 is shown in Fig. 5, in which data from other stations in Antarctica are also shown. Mean annual temperatures were estimated from the 10-m snow temperatures.

The depth of density 550 kg/m^3 increases with decreasing temperature, and the slope increases too. However, the depth is also related to the annual mean accumulation rate. One of reasons for fluctuations in Fig. 5 is considered to be caused by different accumulation rates among the stations.

5. Discussion

The strain rate $\dot{\varepsilon}$ of snow densification was expressed by YOSIDA *et al.* (1956) and BADER (1960) as

$$\dot{\varepsilon}=-\frac{1}{\rho}\frac{d\rho}{dt}=-\frac{\sigma}{\eta}, \tag{1}$$

where ρ and t are density and time, σ and η are pressure of the overlying snow and compactive viscosity coefficient, respectively. BADER (1962) used a hyperbolic-sine function for pressure, to include high pressures. However, a linear relation has been found below approximately 1×10^5 Pa, and the pressure range of the overlying snow for the initial stage of densification is less than 1×10^5 Pa in this work.

The compactive viscosity coefficient η is expressed as

$$\eta=\eta_0 \exp(b\rho)\exp\left(\frac{E}{kT}\right), \tag{2}$$

where T and k are temperature and Boltzmann's constant, η_0, b and E are constants. For Antarctic snow $b=2.40\times10^{-2}$ m^3/kg and $E=50$ kJ/mol (KOJIMA, 1964).

According to Sorge's law (BADER, 1954) the relation between the density ρ and the depth h is invariant with time t at constant accumulation rate A and temperature. Therefore,

$$\sigma=\int_0^h \rho \mathrm{d}h=At, \tag{3}$$

and from eq. (1),

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

Integrating eq. (4) from the surface, we obtain

$$\sigma=\left[2A\eta_0 \exp\left(\frac{E}{kT}\right)\{E_i(b\rho)-E_i(b\rho_0)\}\right]^{1/2}, \tag{5}$$

where ρ_0 is the surface density and $E_i(x)$ is the exponential integral which is defined as

$$E_i(x)=\int_{-\infty}^{x}\frac{e^u \mathrm{d}u}{u}. \tag{6}$$

Equation (5) shows that the pressure of the overlying snow at any density is obtained from the accumulation rate A, temperature T and densities ρ and ρ_0.

Estimated pressure of the overlying snow is shown as a function of density in Fig. 6. The compactive viscosity coefficient, calculated from the lines fitted to the observed data, are plotted against density in Fig. 7. In the analyses the calculation was made for an interval of $\Delta\sigma=500$ kg/m^3.

The value of $\log\eta$ increases linearly with density below about 550 kg/m^3. The slope corresponds to values of b as follows: $b=2.40\times10^{-2}$ m^3/kg at S18, 2.83×10^{-2} m^3/kg at W′200, 2.53×10^{-2} m^3/kg at U234 and 2.52×10^{-2} m^3/kg at V142. The average value is 2.57×10^{-2} m^3/kg, slightly larger than the value of 2.40×10^{-2} m^3/kg obtained by KOJIMA (1964). The decrease in η above 650 kg/m^3 at S18 is considered to be caused by some change in the climate, as noticed earlier in the density-depth curve in Fig. 3.

Values of η at 500 kg/m^3 were 1.78×10^{13} N·s/m^2 at S18, 6.32×10^{13} N·s/m^2 at W′200, 1.32×10^{14} N·s/m^2 at U234 and 5.47×10^{14} N·s/m^2 at V142, which are shown plotted against mean annual temperature in Fig. 8. Comparing with eq. (2), E is estimated to be 51.6 kJ/mol, which is almost the same as that obtained by KOJIMA (1964). The best value of η_0 is thus determined to be 1.20×10^{-3} N·s/m^2 from the data at the four stations.

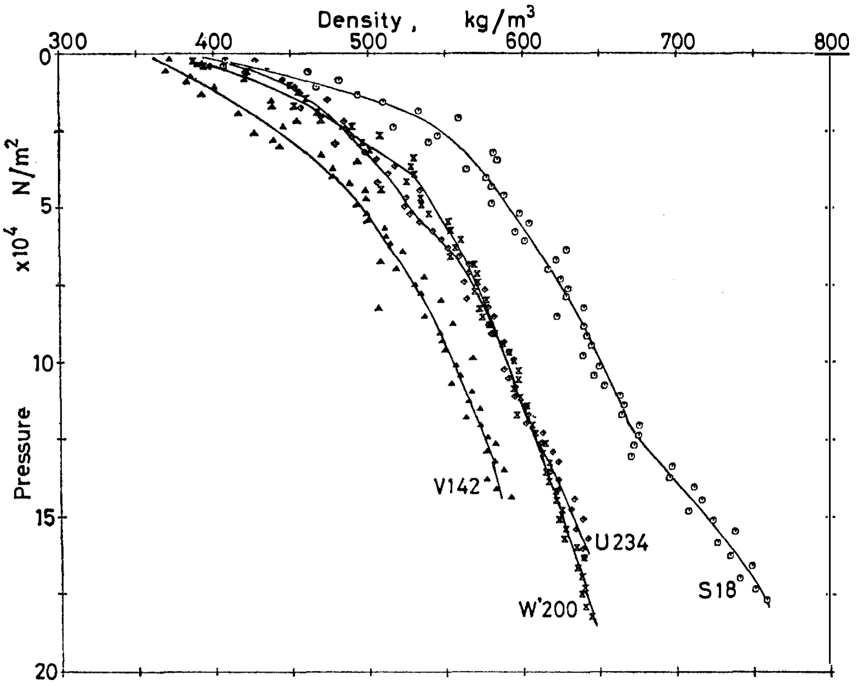

Fig. 6. Profiles of density-pressure of overlying snow at S18, W'200, U234 and V142.

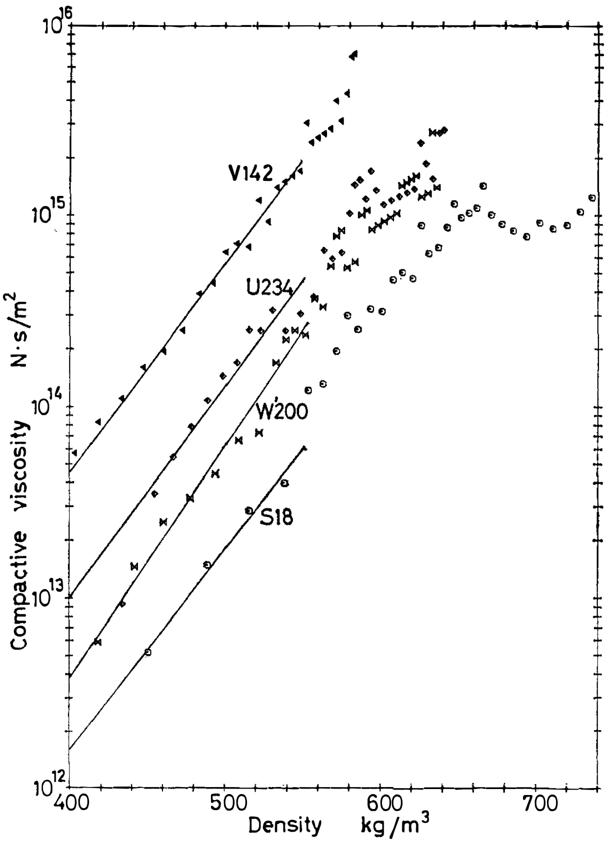

Fig. 7. Relation between compactive viscosity coefficient η *and density* ρ *at S18, W'200, U234 and V142.*

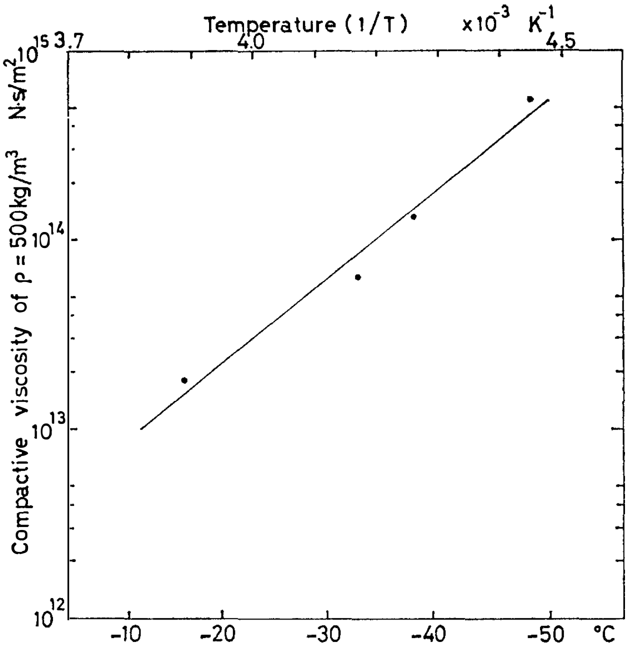

Fig. 8. *Compactive viscosity coefficient η at the density 500 kg/m³ versus the reciprocal of the Kelvin temperature 1/T.*

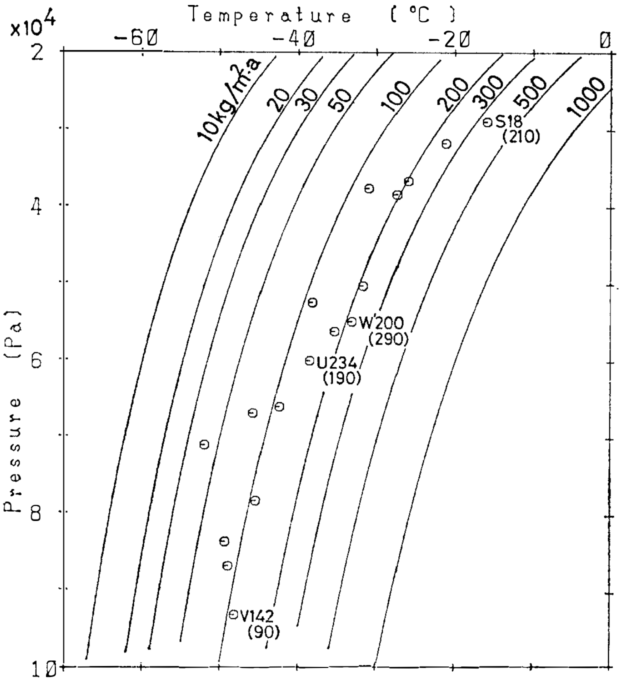

Fig. 9. *Computed results of the relationship between the pressure of overlying snow for the critical density 550 kg/m³, and mean annual temperature, and annual accumulation rate (smoothed curves). Plots indicate observed values at Mizuho Plateau stations. Numbers in parentheses denote the accumulation rate (kg/m³·a).*

If the surface density ρ_0 is set as the average of those in the 0–1 m depth range at the four stations, namely 400 kg/m³, the pressure at the depth of the critical density 550 kg/m³ can be estimated from eq. (5). It is plotted in Fig. 9 as a function of the annual mean temperature and the accumulation rate. This pressure increases with decreasing temperature or increasing accumulation rate. Observed data at Mizuho Plateau (Fig. 5) are also plotted in Fig. 9. The fluctuations noted in Figs. 4 and 5 can now be explained as being caused mainly by the regional differences in accumulation rate.

It is suggested from the above results that if the pressure at which the density 550 kg/m^3 occurs and the mean annual temperature are known, the mean annual accumulation rate over a time scale from 10 to 100 years can be calculated by using Fig. 9. This conclusion seems very useful for estimating past glaciological and meteorological conditions both on the Mizuho Plateau and probably in other polar regions.

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