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Parameters influencing the recrystallization rate of snow

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Abstract

Analysis of experimental data on snow recrystallization under various conditions shows that some components have been omitted in the presently accepted theoretical interpretations and semi-empirical models of the metamorphic process in snow. The observed recrystallization rates related to volumetric mass production, temperature gradient, and temperature are presented. An explanation of the experimental results is proposed in terms of the mass exchange inside a diffusion field of an individual cell of the ice matrix (not necessarily resulting in a crystal size increase) and the mass exchange between the diffusion fields (resulting in change in crystal size). Such interpretation can be used for a combined physical description of the equilibrium and kinetic metamorphism for different types of snow.

Keywords: Snow metamorphism; Recrystallization rate; Heat- and mass-transfer; Volumetric mass production; Acceleration of gravity

1. Introduction

Study of the snow recrystallization process and its relation to heat- and mass-transfer in snow has had a long history and has resulted in a relatively large published literature. However, few of the results can be directly incorporated into "general" environmental science and engineering applications.

The end-user of a "general" model is not interested in specific features of changing grain and bond dimensions. The end-user is concerned with how the in situ meteorological measurements, or remotely observed optical characteristics of snow cover, can be used to estimate the amount of heat and mass transported through or released in a snowpack, and how this energy might change the measurable snow properties. Moreover, the present computer simulations of environmental processes can only include a limited number of snow cover characteristics. Therefore, modeling of the natural processes related to snow cover evolution involves the "effective" characteristics of snow, accepted as sufficient for the usual scales and accuracy of complex environmental models.

Snow characteristics normally considered in models are: (i) The effective heat conductivity of snow (Sturm et al., 1997), with various modifications accepted as responsible for the energy exchange between the Earth surface and the atmosphere in the presence of the snow cover. This characteristic is also included in models of soil freezing processes (Zhang et al., 1996) and in the construction of the Land Surface Schemes of climate models (Loth and Graf, 1998). (ii) Structural characteristics of the snow

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cover, typically in the form of a crystal size distribution, used, for example, in emissivity models of the snow cover (Wiesmann et al., 2000). (iii) The diffusion and convective characteristics of cold snowpacks, involved in the interpretation of ice cores regarding their paleo-temperature and chemical information (Schwander, 1996). All three are related to each other but are rarely considered in a combined description of snow cover evolution.

"Effectiveness" of the parameters used in models is also involved in the most detailed physical models of the snow cover evolution, through their semi-empirical descriptions of the interrelationships between various snow characteristics (Brun et al., 1997; Hardy et al., 1999; Lehning et al., 1999). For example, the processes representing the recrystallization activity in snow are often represented by a formalized snow evolution classification rather than in terms of the physical processes involved. The snow evolution is expressed in terms of bond and crystal size, combined with crystal shape, expressed in terms of the sphericity or dendricity of the crystals. The shape estimate is extracted from results of observations in a selected area (Brun et al., 1992) and based on empirical models of temperature- and temperature gradient-dependent changes of crystal size with time (Bartelt et al., 2000; Gubler, 1998). Approximation of experimental data may correspond to specific experimental conditions only (such as those of Marbouty, 1980 or Baunach et al., 2001). Though formalization provides a path around some uncertainties in the present physical understanding of the snow cover evolution, it can result in inaccuracies due to the absence of some components (Colbeck, 1982) that have been shown to be important under other experimental and environmental conditions (Sokratov et al., 1999). This can explain the reported discrepancies between the modeled and the observed equilibrium (Brown, 1999) and kinetic (Baunach et al., 2001) recrystallization rates. These discrepancies are not accounted for by the snow characteristics used in the studies identified above.

2. Recrystallization rate

Among the four primary parameters determined necessary for description of the snow microstructure (Bartelt et al., 2000), only one, i.e. grain *diameter*, was measured in all the investigations cited below. Accordingly, in this paper, "crystal size" refers to the "*diameter* of a circle with an area equal to the area occupied by a crystal on an analyzed microphotograph" and a "recrystallization (growth) rate" refers to the "change of such areas with respect to time".

In the absence of melting, the ice crystals observed in snow generally increase in volume with time, while total surface free energy decreases. Small grains disappear and large grains grow. However, this is an idealized interpretation of the process, different at each of the three following stages.

(i) The initial *precipitation particles*, immediately after deposition, suffer "destructive metamorphism", where particles with complicated shapes are transformed into geometrically simple shapes known as *grains* (Yosida, 1955).

(ii) The grains do not simply grow in size, but often change their form (for example to *faceted crystals*). The rate of this process normally decreases with time. Fully developed depth hoar is believed to correspond to a certain density of snow for specific conditions (Giddings and LaChapelle, 1962).

(iii) With decreasing growth rate, the faceted crystals again round off as required by the low recrystallization-rate equilibrium form (Colbeck, 1983).

The complexity of the recrystallization rate definition for fresh snow and the absence of reported experimental results on the depth hoar transformation back to rounded grains did not allow consideration of all three stages of snow metamorphism as a continuous process.

In addition, the difference in the aims of the investigations of dry snow metamorphism resulted in a division of the metamorphic process into two distinct approaches—considerations of the *equilibrium metamorphism*, often with the snow crystals approximated as rounded grains, and considerations of the *kinetic metamorphism*, normally related to the depth hoar (faceted crystals) formation under a temperature gradient (Colbeck, 1982). In relation to the stages of the snow cover evolution listed above, kinetic metamorphism is normally associated with the upper layers of a snow cover, while below the layer with daily temperature variations, snow recrystallization is often related to conditions of equilibrium metamorphism.

2.1. Equilibrium recrystallization

At present, there are two "scales" of consideration for equilibrium snow grain evolution. The first one is based on the idea of sintering (Atkinson and Rickinson, 1991) and considers the formation of bonds between ice particles. For snow, many aspects of the phenomenon were analyzed (Colbeck, 1998; Eluszkiewicz et al., 1998; Maeno and Ebinuma, 1983), but the resulting theories cannot yet be applied to snow recrystallization rates reported in the literature because of the low accuracy of the measurements and the high quantity of environmental parameters acting in both natural and laboratory experimental conditions. The second scale, corresponding to the empirical formulations recently used, is based on proposed snow cover classifications (Colbeck et al., 1990; Sommerfeld, 1970). At this scale, the recrystallization rate as defined above can be accepted.

It was expected that the equilibrium recrystallization would depend on temperature (T) and on the difference in the water vapor pressures near a crystal surface (p_s) and in the surrounding environment of the pore space (p_e). The mass balance on the surface was represented by the Knudsen–Langmuir equation (Sokratov et al., 2001), following Colbeck (1982). If P is the maximal possible water vapor production or absorption in a unit volume of snow, α is the evaporation/condensation coefficient of the surface of an ice matrix, S is the specific surface area of snow, m is the mass of water molecule, and k is Boltzmann's constant, then:

$$P = \alpha(p_s - p_e) S \sqrt{\frac{m}{2\pi kT}} \,. \tag{1}$$

The reason for the water vapor pressure difference was assumed to be a result of the difference in the surface curvature of the grains (Brown et al., 1994; Colbeck, 1980).

For aged firn (rounded grains with low porosity), the curvature difference can hardly be a driving force in the recrystallization process. However, the recently observed temperature fields around individual crystals growing in supercooled water (Braslavsky and Lipson, 1998; Notcovich et al., 1999), when applied to ice crystals growing in air (Fujino and Tsushima, 1998), allows the water vapor pressure difference in Eq. (1) to be enhanced relative to the presently accepted curvature-based values due to a temperature difference between the ice surface and the pore space. If such a temperature difference is accepted as a driving force, instead of the curvature effects, the recrystallization rates correlate linearly with P, which is temperature-dependent (Sokratov et al., 2001) (Fig. 1). Half of the specific surface area can be subject to evaporation and half can be subject to condensation. As a first approximation, $P/2$ was assumed for the construction of the figure. The values of $P/2$ were calculated based on the assumption that the experimentally observed increase of the water vapor condensation coefficient on an ice surface with a temperature decrease (Brown et al., 1996; Chaix et al., 1998) was compensated for in Eq. (1) by the decrease of the expected temperatures (and water vapor pressures) difference between the crystals surface and the pore space. The latter is a result of the mass-exchange activity, depending on the water vapor amount in the pore space, which decreases with the temperature decrease. This allows us to accept that the value of $\alpha(p_s - p_e)$ is uniform over the entire temperature range and corresponds to the only one so far observed experimentally by Fujino and Tsushima (1998).

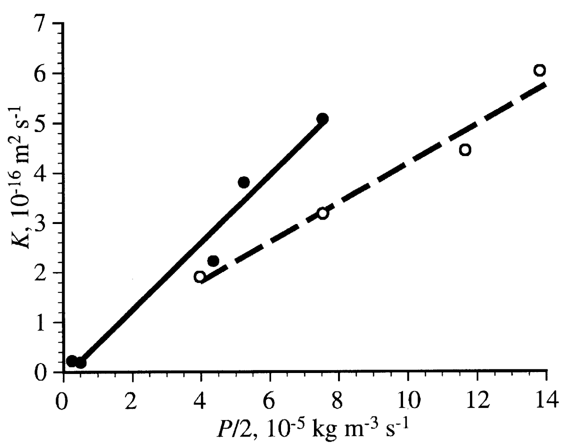

Fig. 1. Relationship between the reported equilibrium recrystallization rates (Gow, 1974) (K) in aged firn and the water vapor production ($P/2$). (●) and (○) stand for different methods of grain size determination.

Despite intensive theoretical analysis, almost no experimental results on the equilibrium metamorphism of "new" snow (opposite to the "aged" firn as in Fig. 1, i.e. with low sphericity and high dendricity) have been reported. The results cited by Yen (1981), after Yosida (1955), showed that the recrystallization rate of fresh-fallen snow at -20 °C was approximately 60% of the recrystallization rate at -6 °C. A similar ratio was observed in recrystallization experiments under equilibrium recrystallization (Kamata, in preparation). Such results indicate that Eq. (1) is not acceptable for the description of the process of the "new" snow recrystallization. If that were the case, the recrystallization rate of "new" snow at -20 °C would be approximately 30% of that at -6 °C. On the other hand, the data on the dependence of crystal-size-change on temperature presented by Marbouty (1980) gave the recrystallization rate at -20 °C as only 9% of that measured at -6 °C (if the square of the grain diameters is considered). However, those results were obtained under temperature gradient conditions.

The recrystallization rate in natural snow can additionally be modeled as a function of a statistical distribution of grains and pores sizes, where both characteristics change with time (Brown et al., 1997, 1999). For "new" snow, the difference between the theoretical (without size distribution) and the observed K could be about two orders magnitude (Nishimura and Maeno, 1988). The temperature dependence of the recrystallization rates of snow crystals with complicated forms more likely includes some additional parameters, responsible for the processes taking place inside the diffusion fields of individual snow crystals and for the mass exchange between the diffusion fields and the air in the snow pore space. Reported uncertainties relating to the statistical distributions of crystal sizes to recrystallization rates might be caused by omitting the specific processes of diffusion field interactions in the corresponding models.

2.2. Temperature gradient recrystallization

The considerations of the temperature gradient (kinetic) recrystallization cannot be separated from the description of the heat-flux in snow (q). The latter, under quasi-steady state conditions, is normally defined as (Colbeck, 1982):

$$q = -k_i \frac{\partial T}{\partial y} + LF, \tag{2}$$

where k_i is the heat conductivity of the ice matrix, y is the coordinate in the direction of flux, L is the latent heat of sublimation, and F is the water vapor flux. For the quasi-steady state conditions, and without volumetric mass production, the water vapor flux can be written as (Sokratov and Maeno, 2000):

$$F = -\phi \frac{f}{\tau} D_a \frac{\partial C}{\partial T} \frac{\partial T}{\partial y}, \tag{3}$$

where ϕ is the snow porosity, f is the gradient enhancement factor, τ is the tortuosity, D_a is the water vapor diffusion coefficient in air, and C is the water vapor concentration in the pore space of snow.

Presently accepted and experimentally confirmed conclusions on the behavior of the temperature gradient recrystallization are: (1) The recrystallization of snow leads to the formation of solid-type depth hoar under temperature gradient less than 25 °C m^{-1}, and skeleton-type depth hoar under larger temperature gradients; if the temperature gradient exceeds some density-dependent value, the recrystallization process increases the snow hardness due to cementation of depth hoar crystals by bonds and small grains (Akitaya, 1974). (2) The strength of snow with time was observed to weaken at the beginning of depth hoar formation and the depth hoar layers formed appear to strengthen later (Bradley et al., 1977). (3) The recrystallization rate increases with increasing temperature gradients up to some limiting value (Pahaut and Marbouty, 1981) and decreases with decreasing temperature (Delsol et al., 1978; Marbouty, 1980; Pahaut and Marbouty, 1981). This dual rate dependence was later interpreted as the recrystallization rate dependence on the water vapor flux characteristics (Armstrong, 1985; Kamata et al., 1999b), where the relative importance of temperature gradient was large when the temperature was high and was negligible for low temperatures (Kamata et al., 1999a). (4) The recrystallization rate decreases with density increase and (5) the recrystallization rate dependence on temperature is less pronounced for a higher snow density (Delsol et al., 1978; Marbouty, 1980; Pahaut and Marbouty, 1981). (6) The recrystallization rate decreases with time and with increase in crystal size (Baunach et al., 2001; Sturm and Benson, 1997).

Existing models of crystals growth rate do not consider all the features cited above. For example, the model presented by Marbouty (1980) does not represent the recrystallization rate decrease with time. The more accurate Baunach et al. (2001) model fails under high temperature gradient conditions. The difficulty in modeling all of these behaviors stems from the extremely limited amount of data available for construction of such descriptions. The results of different investigations often cannot be compared.

As a consequence, only recently obtained experimental results (Table 1) are used for the analysis presented here. The experimental procedure and initial data interpretation for data presented in Table 1 are described by Kamata and Sato (1998) and Kamata et al. (1999a,b). For these experiments, use of the same type of snow and a similar duration of the experimental runs allowed the possible effects of structural differences, formed before or during the experiments, to be neglected in the final results.

Table 1
Temperature gradient recrystallization rates (K) of the light compacted snow under temperature gradient conditions[a]

T, °C	$\partial T/\partial y$, K m^{-1}	F, 10^{-6} kg m^{-2} s^{-1}	$\partial F/\partial y$, 10^{-6} kg m^{-3} s^{-1}	P, 10^{-6} kg m^{-3} s^{-1}	K, 10^{-14} m^2 s^{-1}
94 h, downward heat-transfer					
−3.1	−83	−0.30	−2.91	836	39.79
−5.5	−67	−0.22	−0.64	695	35.89
−7.8	−73	−0.18	−0.93	582	28.15
72 h, upward heat-transfer					
−7.1	−56	−0.16	5.16	613	−8.38
−5.3	−60	−0.19	−1.65	709	18.41
−3.2	−64	−0.25	−1.27	829	11.58
72 h, upward heat-transfer					
−24.4	−277	−0.14	0.79	145	5.73
−18.9	−183	−0.20	−3.41	235	7.76
−13.7	−91	−0.16	2.22	365	23.67
54 h, upward heat-transfer					
−56.9	−613	−0.02	−0.85	5.02	2.08
−35.9	−711	−0.10	−3.77	49.3	6.03
−21.6	−408	−0.19	−12.11	185	18.09
56 h, downward heat-transfer					
−27.2	−497	−0.17	−41.5	113	42.86
−40.9	−336	−0.04	−0.83	29.8	8.14
−56.3	−497	−0.01	−0.87	5.36	6.34
156 h, upward heat-transfer; the one corresponding to Sokratov and Maeno (2000)					
−13.1	−3	−0.004	−0.209	286	13.7
−11.2	20	0.039	−7.69	333	15.47
−8.5	−90	−0.221	9.03	413	18.82
−7.5	15	0.040	−6.88	449	11.48
−6.0	−40	−0.118	11.8	502	17.05

[a] The description of the experimental procedure can be found in Kamata and Sato (1998), Kamata et al. (1999a,b), Sokratov and Maeno (2000).

3. Data analysis

The recrystallization data from Table 1, plotted against the temperature (Fig. 2), indicates a decrease of the recrystallization rate (K) with decreasing temperature (T). The temperature dependence is less pronounced than in the case of firn (Fig. 1), but diffusion field effects may explain this difference. The value of P still corresponds to those from Eq. (1) (regardless of the accepted reasons for the water vapor pressure difference). However, the more "complex" a crystal surface is, the higher is the temperature variation expected along the crystal surface. Also, a larger part of P can remain inside the diffusion field of this individual cell of the ice matrix, leading to mass redistribution on the corresponding grain, instead of it taking part in the mass exchange between grains. This water vapor can change the shape of the crystal, but not its volume. Naming this part of the water vapor production P_f, the observed recrystallization rates should correlate not with P but with $P - P_f$. In the case of temperature gradient conditions, both terms (P and P_f) are affected by: the gradient of the water vapor flux ($\partial F/\partial y$), the amount of locally transferred water vapor (F), the temperature gradients and temperatures in the ice matrix and in the pore space of snow.

The existing data is insufficient for a multidimensional analysis. However, following Delsol et al. (1978), it is possible to estimate the effects listed above separately. Though the resulting dependencies cannot be very accurate numerically, they may show trends responsible for the recrystallization rates component. The results of such an analysis are shown below.

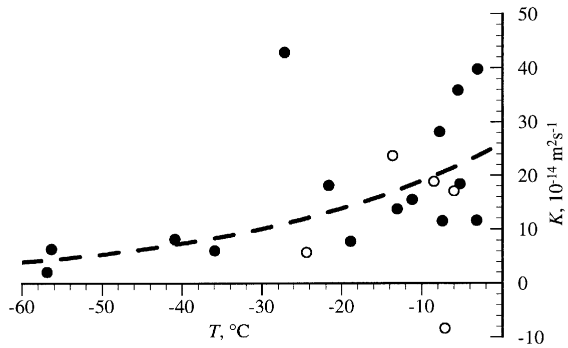

Fig. 2. Observed recrystallization rates (K), (●)—for the conditions of prevailing condensation ($\partial F/\partial y < 0$) and (○)—prevailing evaporation ($\partial F/\partial y > 0$), plotted against the observed quasi-steady-state temperatures (T).

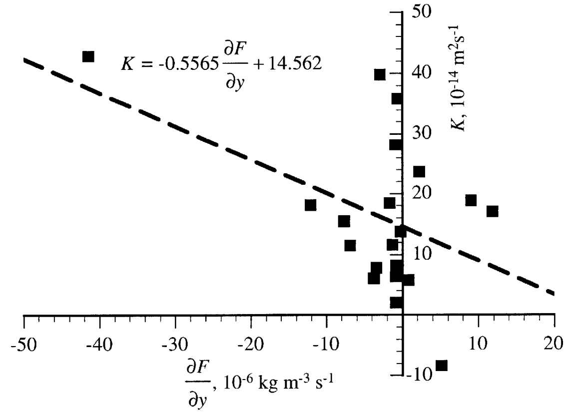

Fig. 3. Observed recrystallization rates (K) plotted against $\partial F/\partial y$, estimated from the experimental results by Eq. (3).

3.1. Water vapor flux gradient

The influence of the water vapor flux gradient ($\partial F/\partial y$) is noticeable even for the raw data presented in Table 1 (see Fig. 3). An increase in condensation, caused by a flux of external water vapor ($\partial F/\partial y < 0$), causes an increase in the recrystallization rate. Conversely, an increase in evaporation ($\partial F/\partial y > 0$) within the snow layer causes a decrease in the recrystallization rate. Considering the experimental set-up used in these investigations, the flux gradient effects may provide an additional explanation of the lower recrystallization rates close to 0 °C (evaporation near the heat source) compared with around −6 °C, reported in Delsol et al. (1978), Marbouty (1980) and Pahaut and Marbouty (1981).

The experimental data can be adjusted to $\partial F/\partial y = 0$ according to the linear dependence shown by the regression line in Fig. 3. However, as discussed in Sokratov et al. (2001), comparisons indicated that there had to be at least one additional water-vapor-effect, related to the conditions of prevailing evaporation or prevailing condensation in a snow layer, because for a "given" $\partial F/\partial y$, the ratio $(\partial F/\partial y)/P$ can vary. The latter, corresponding to the ratio be-

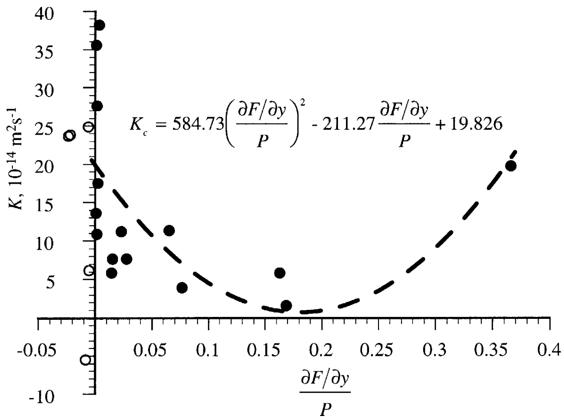

Fig. 4. Recrystallization rates (K) adjusted according to the regression line in Fig. 3, (●)—for the condition of prevailing condensation (K_c) and (○)—for the conditions of prevailing evaporation, plotted against $(\partial F/\partial y)/P$, estimated from the experimental results by Eqs. (1) and (3).

tween a part of the specific surface area subjected to condensation (S_c) and a part subjected to evaporation (S_e), has to influence the recrystallization rates observed. For $\partial F/\partial y = 0$, the ratio of the areas should be 1. For $0 < |\partial F/\partial y| < P/2$, as was the case in our experiments,[1] the simplest representation of this ratio is:

$$\frac{S_c}{S_e} = \frac{n_c}{n_e} = \left(\frac{1}{2} + \frac{\partial F}{\partial y}\Big/P\right)\Big/\left(\frac{1}{2} - \frac{\partial F}{\partial y}\Big/P\right), \qquad (4)$$

where n_c and n_e represent quantities of growing and evaporating snow crystals in a unit volume of snow, respectively.

For the measured data, it was possible to relate the recrystallization rates and $(\partial F/\partial y)/P$ directly. This is shown in Fig. 4.

The recrystallization rates under condensation conditions can be also reasonably explained by considerations of the diffusion field. Water vapor incoming from other parts of a snow sample, on one hand, can enhance the crystal growth (Fig. 3), increasing the ratio presented in Eq. (4) and P values relative to the equilibrium conditions $(P/2)$. On the other hand, unless the mass exchange is mainly regulated by this excess water vapor (a sufficiently large $(\partial F/\partial y)/P$), the mass exchange between the diffusion fields of individual components of the ice matrix, i.e. the crystal growth, can be suppressed by the "excess" water vapor in the surrounding pore space. The summarized effects result in the relationship for the recrystallization rates with condensation (K_c) presented in Fig. 4.

For evaporation, the form of the dependence will most likely be opposite to that of K_c. However, almost no such conditions could be analyzed in our experimental runs, and data on recrystallization rate with evaporation (K_e) have to be excluded.

3.2. Temperature gradient

When the recrystallization rates, adjusted according to the trendlines in Figs. 3 and 4 are plotted against the observed quasi-steady-state temperature gradient (Fig. 5), the data can be clearly divided between the K_c observed in the samples with the downward heat- and mass-fluxes $(K_{c\downarrow})$ and the data from samples with the heat- and mass-fluxes directed upward $(K_{c\uparrow})$.

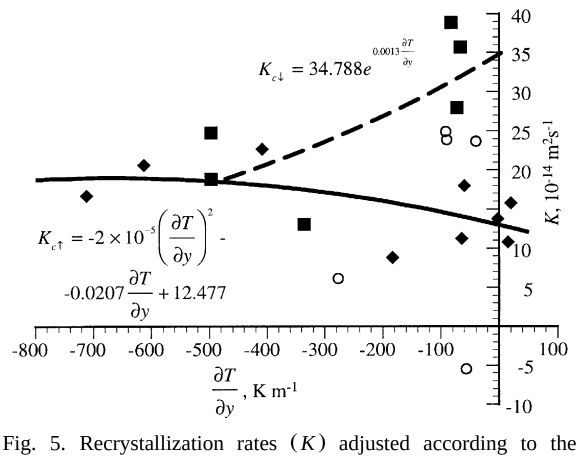

Fig. 5. Recrystallization rates (K) adjusted according to the trendlines in Figs. 3 and 4 for the condition of prevailing condensation with (■)—downward $(K_{c\downarrow})$ and (◆)—upward $(K_{c\uparrow})$ heat- and mass-fluxes, and for the conditions of prevailing evaporation (○), plotted against the observed quasi-steady-state temperature gradients $(\partial T/\partial y)$.

[1] When $|\partial F/\partial y| \geq P/2$, all the ice matrix surface can be subject to evaporation or condensation, and the recrystallization rate can be regulated by the relationships accepted in cloud physics (Hobbs, 1974) rather than by the heat- and mass-transfer descriptions used for Eqs. (2) and (3).

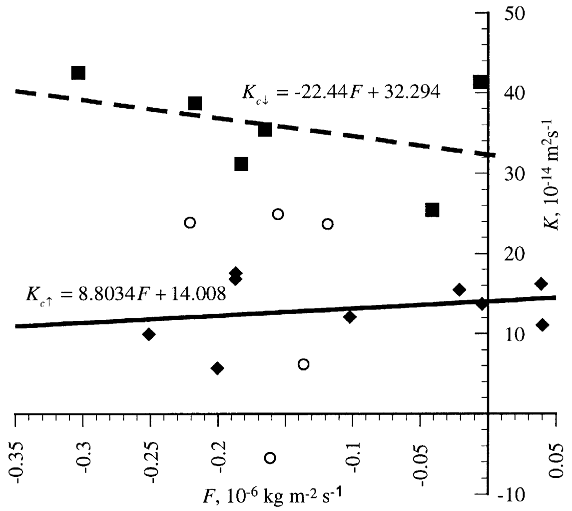

Fig. 6. Recrystallization rates (K) adjusted according to the trendlines in Figs. 3–5 for the condition of prevailing condensation with (■)—downward $(K_{c\downarrow})$ and (♦)—upward $(K_{c\uparrow})$ heat- and mass-fluxes, and for the conditions of prevailing evaporation (○), plotted against the water vapor flux (♦), estimated from the experimental results by Eq. (3).

Under an upward heat-flux, corresponding to the conditions used by Akitaya (1974), the growth rate increases with an increase in temperature gradient up to some limiting value, with no temperature gradient dependence under higher temperature gradients. This lack of temperature gradient dependence can be interpreted in terms of the observations by Akitaya (1974). He observed bond formation instead of crystal growth under sufficiently high temperature gradient. In the "downward-heat-flux" samples, the recrystallization rate decreases with temperature gradient increase, up to approximately the same limit as for $K_{c\uparrow}$, and for higher temperature gradient the difference between $K_{c\downarrow}$ and $K_{c\uparrow}$ was not seen in our data. The most probable explanation for the recrystallization rate difference below the limiting temperature gradients appears to be the acceleration of gravity effect on the directional (under temperature gradient conditions) mass exchange between the diffusion fields of individual ice matrix components. If such an explanation is accepted, the P_f component of P is larger for the upward heat- and mass-transfer. The difference between $K_{c\downarrow}$ and $K_{c\uparrow}$ decreases as the form of the diffusion field is more and more regulated by the temperature gradients formed in the ice matrix and in the pore space.

Water vapor flux has opposite effect on the recrystallization rates in the upward-heat-flux and the downward-heat-flux snow samples (Fig. 6). Relating the dependencies shown in Fig. 5 to the temperature gradient effect on the individual diffusion fields (P), and the water vapor flux effect (Fig. 6) to the $P - P_f$ characteristic, the recrystallization rate should decrease with decreasing water vapor flux. Because this is evident only in the downward-heat-flux data, it indicates that with greater P_f, a "given" water vapor flux has reduced impact on the mass-exchange between the diffusion fields of the individual ice matrix component and that the other parameters become more important.

3.3. Temperature

When the recrystallization data, adjusted by all the above steps, are plotted against the corresponding temperatures (Fig. 7), the behavior is very different from that displayed in Fig. 2. Of course, the results of a detailed multidimensional data analysis may not provide exactly the same response to the temperature dependencies. However, the plots of the parameter effects (Figs. 2–6) have similar form for the raw data, although they are different numerically. The temperature dependence presented in Fig. 7 also can

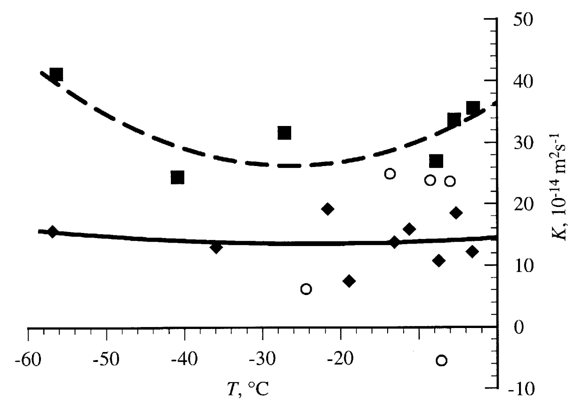

Fig. 7. Recrystallization rates (K) adjusted according to the trendlines in Figs. 3–6 for the condition of prevailing condensation (■)—downward $(K_{c\downarrow})$ and (♦)—upward $(K_{c\uparrow})$ heat- and mass-fluxes, and for the conditions of prevailing evaporation (○), plotted against the observed quasi-steady-state temperatures (T).

be explained with the diffusion field involved. On one hand, the temperature decrease should lower the amount of water vapor being generated (P) and therefore condensing on the ice matrix surface, lowering the recrystallization rate (Fig. 1). On the other hand, the lower the temperature, the thinner the diffusion field around individual component of the ice matrix (P_f) is likely to be. The mass exchange between the neighboring diffusion fields should increase, resulting in more active recrystallization. The form of the temperature dependence shown in Fig. 7 agrees with the result of combining these two opposite effects.

The dependencies are likely to be different in other types of snow. It can be expected that for ice spheres, the temperature dependence will be mainly regulated by P, while for fresh precipitation particles, with relatively small $P - P_f$, the temperature dependence may be less pronounced, though large values of the specific surface area can still result in high recrystallization rates.

The results of the present analysis suggest that the recrystallization rate related only to temperature and temperature gradient will not permit an accurate empirical model of snow cover evolution to be developed. Moreover, the relationships plotted in Fig. 7 suggest a framework to relate the wide range of the experimental results to the effects of other components of the heat- and mass-transfer not previously considered.

4. Conclusions

Introducing the effects of the diffusion field into an analysis of the snow recrystallization process offers an explanation for almost all of the recent results on snow recrystallization rate investigations (see Section 2.2).

(1) The temperature gradient changes the structure of the diffusion field around the components of the ice matrix, making the latter more asymmetrical than under equilibrium conditions (enhancing both P and $P - P_f$). However, while for simple-form grains (firn) this asymmetry should directly influence the recrystallization rate, for "new" snow the temperature gradients on the grain surface can be initially larger than those due to applied external gradients, with the latter being negligible up to some limiting value. This effect can explain the reported lower limit of temperature gradient response resulting in bond formation (Akitaya, 1974).

(2) The recrystallization process results in a decrease of the specific surface area of snow with time (decrease of P) and simplification of the crystal form, relative to the diffusion field structure (decrease of P_f). Thus, the lower limit of the temperature gradient response resulting in bond growth also decreases with time. This decrease correlates with the observations of Bradley et al. (1977).

(3) As the water vapor flux increases, P_f typically decreases. Thus, the recrystallization rate can increase with an increase in water vapor flux (Kamata et al., 1999a).

(4) For a given type of snow and temperature gradient, the greater the snow density, the greater the tortuosity of the pore space (with effects of ϕ and f compensating each other in Eq. (3)). This increase in tortuosity lowers the water vapor component in Eq. (2), decreases $P - P_f$ by increasing P_f, and thus decreases the recrystallization rate, as reported in Delsol et al. (1978), Marbouty (1980) and Pahaut and Marbouty (1981).

(5) As discussed above (point (4)), the higher the snow density, the lower the recrystallization rate, and the less pronounced its temperature dependence is for the data resolution reported in Delsol et al. (1978), Marbouty (1980) and Pahaut and Marbouty (1981).

(6) The observed recrystallization rate decrease and crystals size increase with time appears to correspond to a decrease in the specific surface area of the snow.

(7) Accounting for the wide temperature range corresponding to the recrystallization rates regulated by $P - P_f$ (Fig. 2) relative to that, corresponding to the recrystallization rates regulated by P (Fig. 1; Gow, 1974), the relative variation of K in the first case appears to be less. This can indicate that for low enough temperature the value of P_f might be negligible for any type to snow. If this is the case, the recrystallization rate at such temperatures will correlate directly with the water vapor production, similar to the relationship for rounded grains as described by Eq. (1).

(8) The point (5) above should be expanded by the following comment: In relation to the gradient enhancement factor (Sokratov and Maeno, 2000)—for a given temperature gradient, the higher the snow density, the lower the enhancement of P due to the temperature gradient in the ice matrix. On the other hand, the higher the snow density is, the easier the mass exchange between the diffusion fields of individual components of the ice matrix is. Thus, the recrystallization rate dependence on density should vary for different types of snow and different temperature conditions.

Despite the appearance of new methods, theoretically allowing more accurate and time-dependent recrystallization rate estimation in different types of snow (Brzoska et al., 1999; Hoff et al., 1998; Ozeki et al., 2000), it is likely that an estimation of P_f will only be possible after including snow structure evolution models taking account of crystal size distribution and the crystal types (Brown et al., 1999). From the author's point of view, the results of the analysis presented here should be considered in the modification of such models, through incorporation of the temperature gradient conditions in the recent theories of snow metamorphism.

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