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CONCURRENT ANALYSIS ON DIRT AGGREGATION AND ALBEDO CHANGES ON A MELTING SNOW SURFACE

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Albedo of a dirty snow surface is strongly controlled by the concentration of dirt particles and their behavior (mainly aggregation phenomena) during conditions of the surface melting. The aggregation in fact causes a full or partial overlapping of the particles leading to a decrease of the total surface area of the particles projected on the surface, which in turn increases the surface albedo. A simple conceptual approach to calculate surface albedo with aggregates of dust particles has been presented, which agreed reasonably with the observation. The present approach incorporated the effect of surface morphological change caused by the migration of dust particles on albedo. This change resulted in decrease of surface albedo. The results indicate that the behavior of dust particles on a melting snow surface is an important factor that controls the surface energy budget.

INTRODUCTION

In nature, a snow surface is usually covered with a layer of dirt or scattered particles derived from natural and/or anthropogenic sources. The natural sources include dust storms originating in arid and semiarid areas (Wake and Mayewski, 1993; Wake et al., 1994; Tegen and Fung, 1994), ash fallout associated with volcanic eruptions (Lliboutry, 1956; Eaton, 1964; Conway et al., 1996), dust fall episodes related to catastrophic landslides (Hewitt, 1988), and carbon soot derived from forest fires (Chylek et al., 1992). The anthropogenic sources may be of industrial carbon emission due to electric power generation using fossil fuels (Warren and Clarke, 1990; Grebenets and Fedoseyev, 1992) and the dust blown about due to disturbance of soil by agricultural activities (Tegen and Fung, 1994; Tegen et al., 1996). Previous studies have suggested that dust particles from natural or anthropogenic sources could be transported to snow-covered areas from both local and distant (or global) sources (Windom, 1969; Warren and Wiscombe, 1981; Wake et al., 1994).

Because pure snow is very weakly absorptive, whereas dirt particles are strongly absorptive in the visible wavelength region, even a small amount of dirt on snow strongly reduces surface albedo, which is the ratio of reflected to incident solar radiation. Hence albedo is an important parameter to determine the absorbance of solar radiation at the snow surface. The increase of solar radiation absorption on the surface significantly enhances surface melting since solar radiation is generally the dominant energy source among energy sources (e.g. sensible and latent heat) for melting in many snow and ice covered regions (Knap, 1997; Oerlemans and Knap, 1998). In the Himalayas for example, solar radiation contributes more than 80 percent of the melt-energy (Kohshima et al., 1993), and more than 95percent of ablation occurs during daytime (Ohata and Higuchi, 1980). As the mountainous rivers are mostly snow-fed, snowmelt hydrology is very important for effective and efficient water resources management in mountainous regions.

Albedo is a crucial parameter to determine surface melting, and litle information exists about the variation of albedo on dust-covered or “dirty” snow surfaces. This is because the albedo of dirty snow is very complicated due to a high degree of variability in the concentration of dust particles (Warren and Wiscombe, 1981,1985) and their behavior on the melting surface (Adhikary et al., 1997, 2000). Owing to the nature of dust particles on melting snow, it is important to treat albedo as a spatial and temporal variable because a slight change in surface albedo may significantly alter the total radiation budget of the surface.

Simultaneous observations of dust concentration and the surface albedo are very useful in understanding their relationship. Such observations carried out both in field or laboratory experiments and in natural conditions have been reported in a number of papers (e.g. Kotlyakov and Dolgushin, 1972; Higuchi and Nagoshi, 1977; Ohata et al., 1980; Adhikary et al., 1997, 2000). One of the common, but most important qualitative results is that snow/ice surfaces have a wide range of albedo dependent on the abundance of dust particles that affect solar radiation absorption. As a rule, the albedo of a snow surface decreases with increasing dust concentration until reaching its asymptotic value, and a further increase in concentration does not change the albedo. However, aggregation of dust particles will deteriorate the relationship between initial dust concentration and surface albedo, for which it is important to understand the behavior of particles on a melting snow surface.

Recently, Adhikary et al. (1997) performed a series of dusting experiments (hereafter SDE will be used for the sake of convenience) on a seasonal snow cover with different loadings of soil dust (particles diameter ranging from 0.35 to 0.15 mm). It was observed that with the initial application of dust, the albedo of the snow surface decreased exponentially with increasing dust concentration (Figure 1). This result is consistent with those observed by previous researchers (Higuchi and Nagoshi, 1977; Ohata et al., 1980). The interesting feature of the SDE is a considerable increase of albedo over time. This was particularly evident on dusted surfaces with low dust concentrations. It was also found that the dust particles were aggregated with time on the melting snow surface. The experimental results will be briefly summarized in a later section.

Our main objectives for this paper are (i) to understand the relative importance of the relationship between dust concentration and snow surface albedo, (ii) to investigate the nature of aggregation phenomena of dust particles, and its effects on albedo on a melting snow, based on experimental data (Adhikary et al., 1997).

AGGREGATION OF DUST PARTICLES

Experimental results and analysis

A brief description of SDE and some key results (Adhikary et al., 1997) will be presented here for the readers' convenience. One of the main objectives of the experiments was to obtain data on the nature of dust particles on a melting snow surface, and albedo changes with time. Five sets of artificial dusting experiments on March 21, 23, 24, 26, and April 11, 1995 were performed on a seasonal snow cover (450 m a.s.l.) in central Japan. Each set of the experiments consisted of four to eight hours during the daytime. A relatively dark soil dust (albedos: 0.08 and 0.06 in dry and wet conditions respectively) composed of particles with diameters; 0.35 - 0.15 mm in size was manually spread on seven plots (25 x 25 cm each in size) for each experiment. Concentrations used for the experiments were 0.056 (P1), 0.080 (P2), 0.112 (P3), 0.160 (P4), 0.224 (P5), 0.448 (P6) and 0.896 (P7) kg m^{-2}. Besides the seven dusted plots, an approximate area of 50 x 50 cm of the snow cover about 1 m away from the nearest dusted surface was monitored as an undusted reference plot. The albedo of the dusted and the undusted snow areas was measured hourly. Photographs of each plot were taken in order to monitor the behavior of dust particles and areal

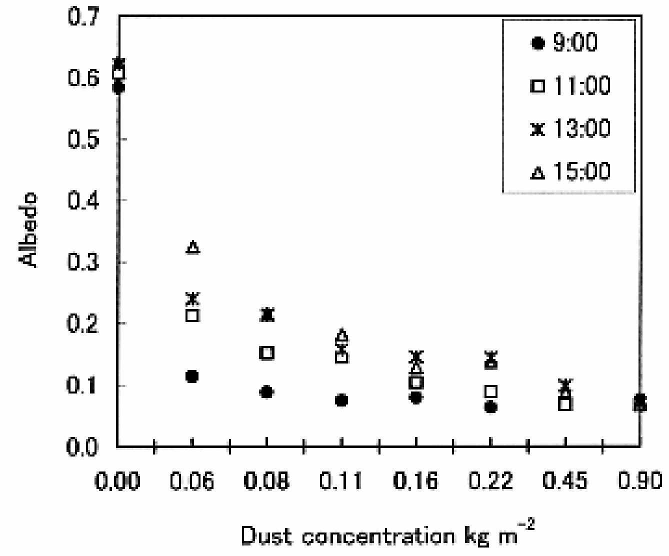

Figure 1. Relationship between dust concentration and albedo of a snow surface at different times. Modified after Adhikary et al. (1997).

ratio of the dust cover on the melting snow surface. Due to a deficiency in photography, not all the photographs were able to detect or analyze the particle behavior; however, photographs from March 23 were of relatively good quality. Details of the instrumentation and the methods of observation are given in Adhikary et al. (1997).

Figure 1 shows the relationship between dust concentration and albedo for different times as an example. The albedo of the snow surface generally decreased exponentially with increasing dust concentration. As time progressed, the albedo of the surface increased, as is more evident on lighter dust concentrations. In other words, the increasing trend of albedo slowed towards the plots with higher dust concentrations, where the probability of masking a greater surface area by dust particles is higher. This figure also indicates the approximate range of dust concentration that would be of special importance regarding the variation of albedo in space and time during snowmelt conditions. For a bare melting snow surface, the albedo was nearly constant (≈ 0.6).

Figure 2 shows a time series photographs of P1 taken during the experiment as an example. It is clear that dust particles started to aggregate after the dusting and proceeded gradually at later times. The aggregation resulted in a decrease of areal fraction of the dust-covered area, which corresponds to the increase of albedo with time as shown in Figure 1. This result indicates that particles on a melting snow surface are affected by meltwater, and the decrease of the areal ratio of dust cover leads to a dramatic increase of snow surface albedo. To evaluate the time variation of representative areal coverage by aggregated groups of the particles, the fractional size of the black parts along 4 profiles (L1 to L4 in Figure 3) across the plot (P1), each spacing 5 cm apart within the plot, have been measured from the photographs (Figure 2). Figure 3 shows a one-dimensional view of the aggregates obtained from Figure 2 and indicates that particles were progressively aggregated as groups with time. Consequently, only about 50 percent of the plot area appeared to be covered by the dust at the end of the experiment. This would obviously lead to

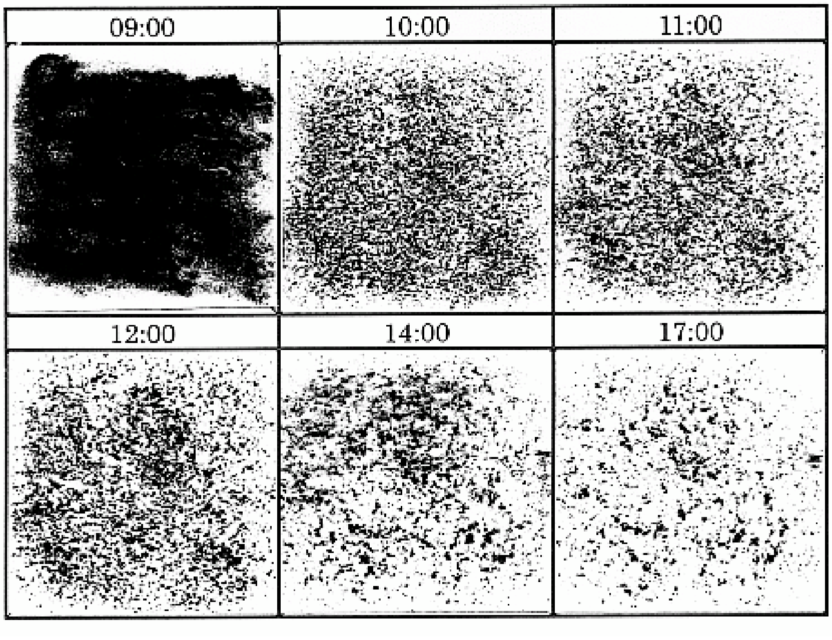

Figure 2. Photographs showing an example of progressive aggregation of dust particles on a melting snow surface. The dust was distributed on the snow shortly before 09:00 when the concentration was 0.056 kg m^{-2} (reproduced from Adhikary et al., 1997, Figure 7a).

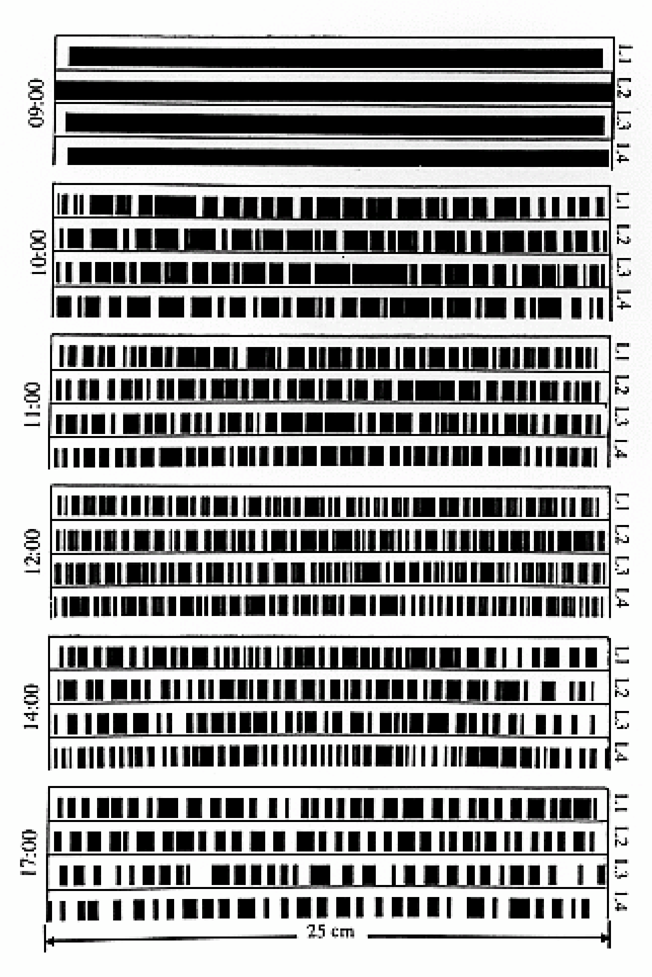

Figure 3. Areal fractions of dust across the plot measured from photographs (Figure 2) along the profiles L1 to L4, each spacing 5 cm apart within the plot.

dramatic changes in surface albedo corresponding to the decreasing trend of the fractional coverage of dust down to 50 percent.

Analysis of fractional size distribution of the aggregates

In order to analyze size distribution of the aggregates, fractional size of the aggregates was measured with time for P1 to P6. The particles did not aggregate at all on P7 during the experiments. Figure 4 shows the frequency distribution of the size of aggregates with time for various degrees of dust concentration. On P1, the fractional size (d) of the aggregates ranged between 0.8 to 25 mm ($0.8 \leq d < 25$ mm), exhibiting a peak frequency at around 2.5 mm. With increasing dust concentration, both the range of the fractional size and the occurrence of peak frequency of the aggregates generally shifted towards higher values. Note that the horizontal scale of each sub-figure in Figure 4 is different. Fractional size of the aggregates on P6 ranged from about 0.8 to 200 mm ($0.8 \leq d < 200$ mm) where peak frequency appeared at around 10 mm. This value is greater by a factor of 4 compared to the value obtained for P1. Comparing P1 to P6, it can also be seen that the magnitude of each value of the peak frequencies among different hours (10:00 to 17:00) appeared the highest (except on P1) at 17:00. The peak frequencies decreased with increasing dust concentration, i.e. the higher the dust concentration, the smaller the magnitude of the peak frequencies.

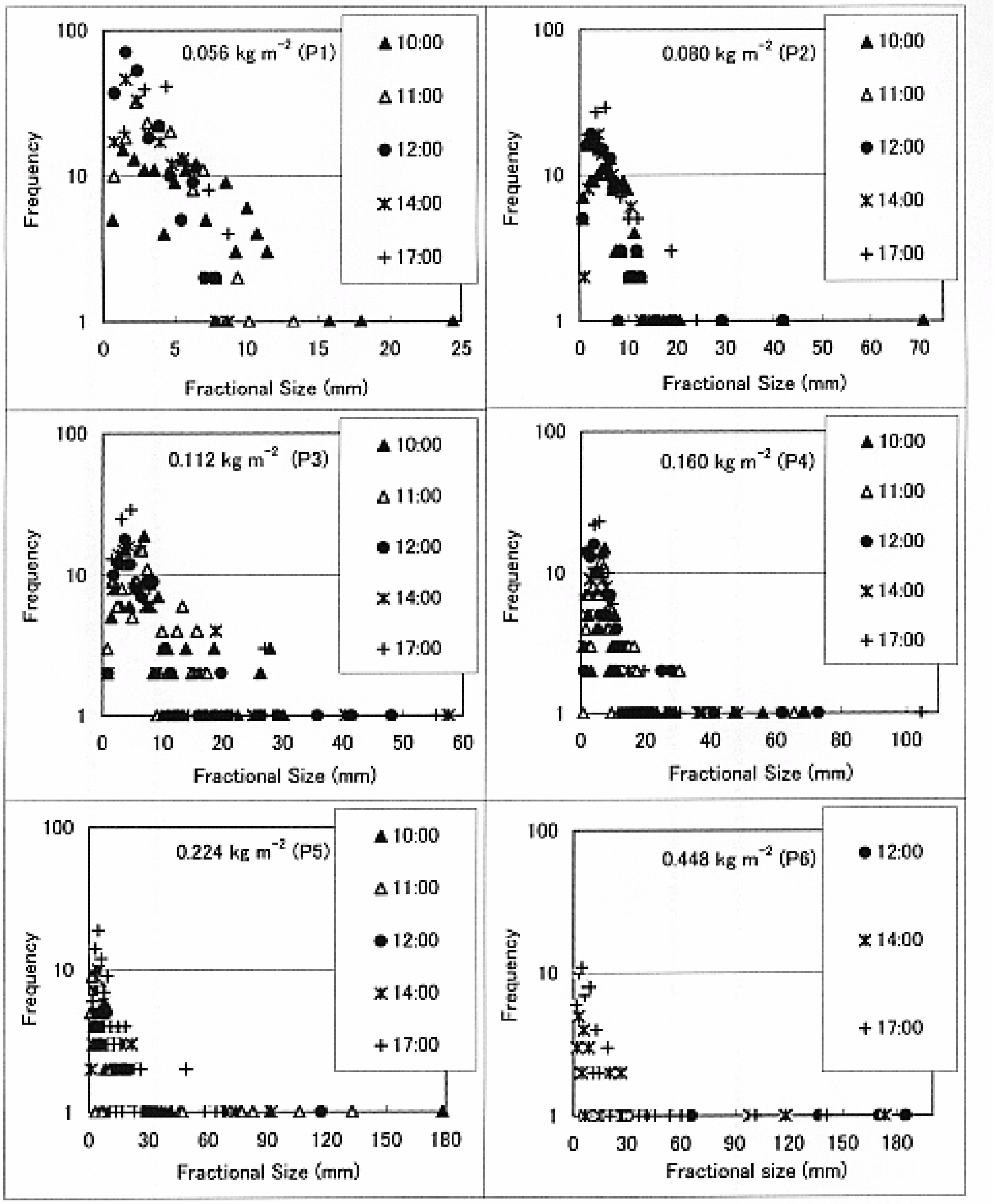

Figure 4. Frequency distribution of fractional size of the aggregates, on a melting snow of various degrees of dust concentrated plots, P1 (Figures 2 or 3) to P6.

Such differential features on the fractional size distribution can be dependent on the abundance of particles on a melting snow surface. In addition, available local meltwater was an important factor for redistribution of particles. However, a snow surface is generally more porous than an ice surface. Unlike an ice surface, meltwater on the snow does not usually remain on the surface; instead it percolates through the snow pack (Conway et al., 1996). Particles on a melting snow surface are not usually washed away, but a thin film of water on the melting surface seems to lubricate the particles which move to adjacent spaces. However, for a melting ice surface, particles are usually washed away depending on a surface slope and an amount of meltwater (Adhikary et al., 2000).

The fractional size distribution of aggregates ranging from 0 to 10 mm (0 < d = 10 mm) on P1 to P6 for different times of Figure 4 is rearranged and shown with greater resolution in Figure 5 as an example. After the initial application of dust, the size of the aggregates on P1 was found highly variable in space compared to the rest of the plots (P2 to P6). The peak frequency of the aggregates on P1 was at about 1.75 mm at 12:00 (intense surface melting condition), and increased to about 5 mm by 17:00 (almost no surface melting condition), but the magnitude of the peak frequency (about 70) at 12:00 decreased to about 40 at 17:00. For the rest of the plots, there was no logical variation on the magnitude of the peak frequencies. However, at 17:00 the most abundant size of aggregates on P1 to P6 ranges from about 3 to 6 mm, with an average peak frequency of 5 mm. Evolution of the aggregates on P1 to P6 with time disclosed that the peak frequency for each plot generally shifted towards a greater fractional size until reaching a mean value of around 5 mm. This

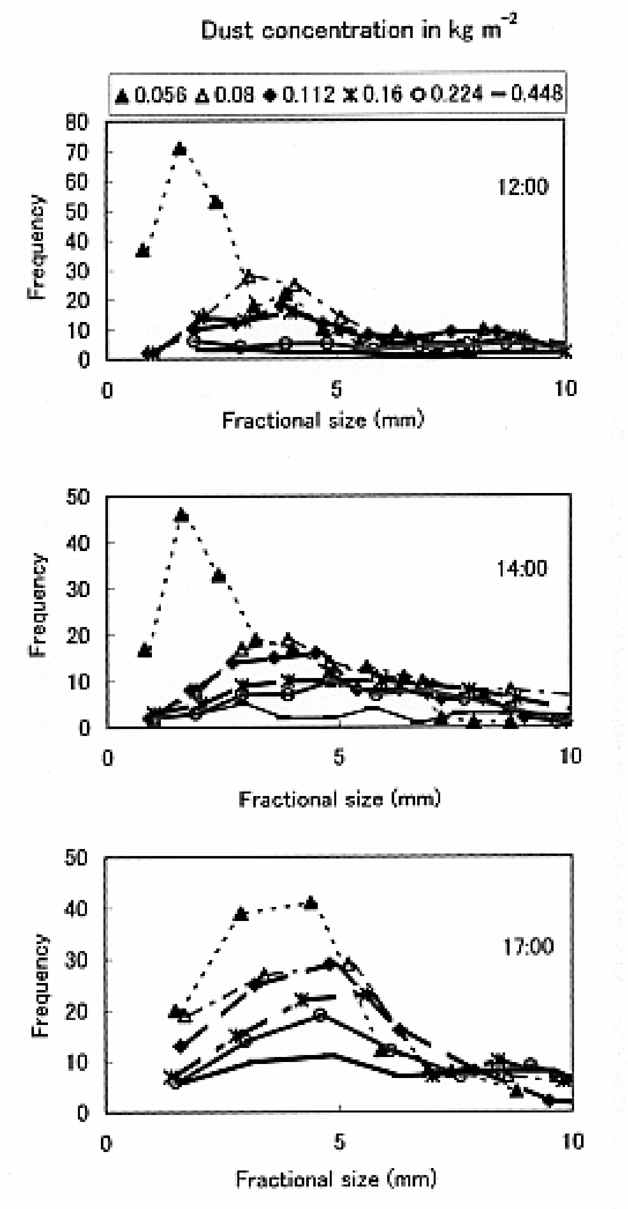

Figure 5. A greater resolution of Figure 4, with some re-arrangements, showing the distribution of fractional size of aggregates ranging from 0 to 10mm with various dust concentration and times.

trend may suggest that aggregates with a smaller number of particles merged with each other, or joined to form a larger aggregate that is relatively more stable.

SHORT-WAVE RADIATION FLUX AND ALBEDO

The surface melting of a snow or ice depends on net energy fluxes. These are a combination of net short-wave radiation, net long wave radiation, and sensible heat and latent heat at the surface. Previous investigators (Ohata and Higuchi, 1980; Mattson and Gardner, 1989; Kohshima et al., 1993; Bintanja et al., 1997; Oerlemans and Knap, 1998), however, found that contribution of net short-wave radiation dominates the energy balance, and hence the melting of snow/ice. Depending on a snow surface albedo, a certain portion of the incoming solar radiation is absorbed by the surface and provides energy for surface melting, while the rest is reflected back to the atmosphere. For a dust covered snow surface, concentration of dust particles and their behavior control albedo (Adhikary et al., 1997, and 2000). Since dust particles have a tendency to aggregate on melting snow, the aggregation process causes an increase in surface albedo that would in turn reduce solar radiation absorption. For example, the amount of solar radiation absorption decreases by more than 20 percent when the albedo increases from 0.1 [typical for a dust-covered (uniform distribution: ≈ 0.06 kg m^{-2}) snow] to 0.3 (nearly upper limit albedo for the surface after the aggregation of dust particles). Hence, the aggregation of dust particles may largely influence the short–wave radiation budget, and it can be a negative feedback for melting.

For a lightly dust-covered snow surface, two different cases of albedo can be considered; first, albedo is relatively constant in space and time (no surface melting condition), and second, albedo is a function of time or the aggregation process (surface melting condition). The latter is of special interest for the purpose of the present study.

Generally, the short-wave radiation budget components and the area-averaged albedo of a snow surface covered with thin or scattered particles can be expressed as,

$$Qs = S{\downarrow} * \left[1 - a(t)\right] \tag{1}$$

$$a(t) = r(t) * \alpha_d + \left[1 - r(t)\right] * \alpha_s \tag{2}$$

Where

Qs : Net short-wave radiation flux (W m^{-2})

$S{\downarrow}$: Incoming solar radiation flux (W m^{-2})

$a(t)$: Average surface albedo as a function of time, t

$r(t)$: Ratio of dust cover at time, t (0 to 1)

α_d : Albedo of dust in wet condition (0.06)

α_s : Average albedo of melting snow prior to the dusting (0.6)

Field experiments revealed that dust particles not only absorb the solar radiation and release it for melting, but also form pits in snow/ice surfsace that collect meltwater (Kotlyakov and Dolgushin, 1972; Adhikary et al., 2000). Such pitted surface morphology leads to an additional decrease of surface albedo, apart from the effect of dust. The additional decrease in albedo is caused by trapping of a certain amount of the incident total solar radiation due to multiple reflection inside the pit and absorption in the meltwater. This additional decrease of albedo imposed by the surface morphology has been taken into account by replacing α_s with α_{s*} in Equation (2). Then,

$$\alpha(t) = r(t) * \alpha_d + [1 - r(t)] * \alpha_{s*} \tag{3}$$

$$\alpha_{s*} = \alpha_s - \alpha_r \tag{4}$$

Where,

α_{s*} : Average albedo of bare snow exposed due to aggregation of dust particles

α_r : Average albedo reduced by the pitted surface morphology

Here, α_r can be estimated experimentally in a small area for the characteristic snow surface, following the calculation of α_{s*} from Equation (3) by averaging with time. That is,

$$\alpha_{s*} \approx \overline{\frac{\alpha(t) - [r(t)] * \alpha_d}{1 - r(t)}} \tag{5}$$

And hence,

$$\alpha_r \approx \alpha_s \overline{\frac{\alpha(t) - [r(t)] * \alpha_d}{1 - r(t)}} \tag{6}$$

Where, over-bars indicate average.

Once α_r is estimated, and $r(t)$, α_d, and α_s are given for the surface in question, one can estimate $\alpha(t)$. Based on the experimental data (Adhikary et al., 1997), α_r has been estimated 0.1 for the present study, which is the average for the experiment duration. It should be noted that α_r is not a constant quantity as α_{s*} is a function of time (Equations 5 and 6). However, after the formation of first phase "radiation brush" (pitting of the snow surface caused by sinking dust particles), it undergoes periodical destruction and reforms again, causing variation on α_r at small times, at least for several hours (Kotlyakov and Dolgushin, 1972). This is the reason that we averaged α_r for the observation period to make the calculation simple, yet reasonably accurate.

MODEL RESULTS AND DISCUSSION

In Figure 6, hourly averaged albedos calculated from Equation (3) and the actually observed albedos are compared for various degrees of dust concentration. With a few exceptions, the calculated albedos tend to be in good agreement with the observed values. For the few latter hours the calculated albedos have been overestimated compared with the observed ones, particularly for light dust concentrations (P1 to P4). The discrepancy between the calculation and the observation on the less dust concentrated plots (P1 to P4) can be explained by possible reasons discussed in the following sections.

Firstly, as the initial loading of dust concentration decreases, the ratio of bare snow due to the aggregation of dust particles increases. This is because particles can migrate freely in a skin layer of the melting snow if the total number of particles is relatively small. In this situation, the

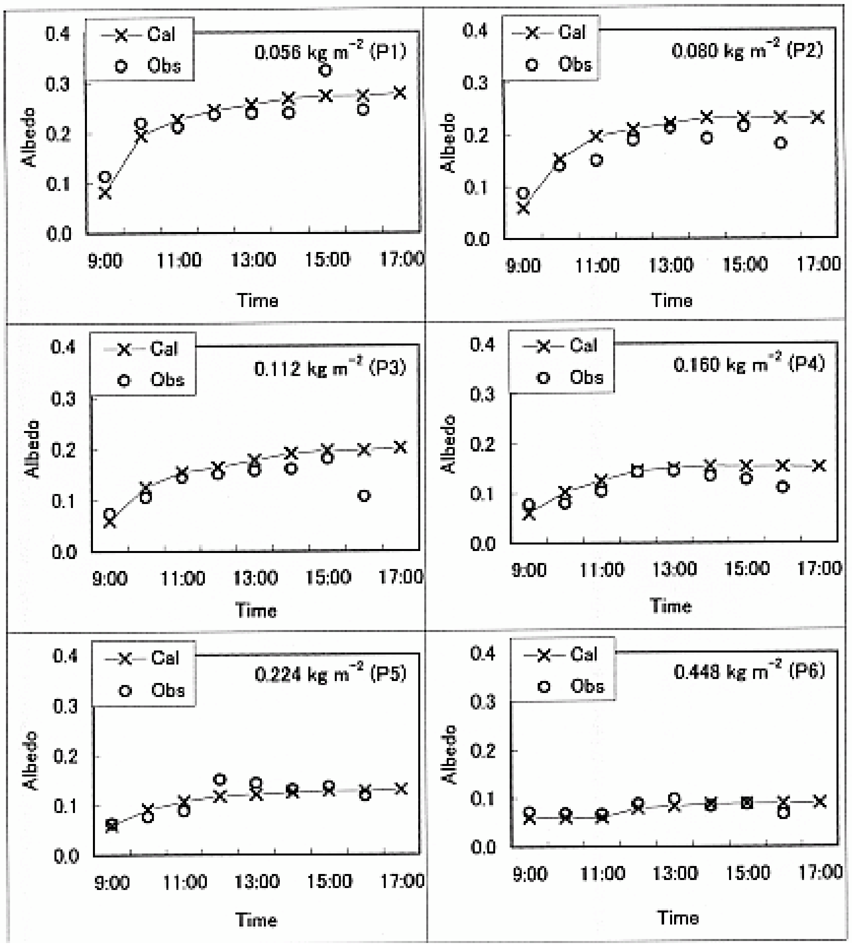

Figure 6. Observed and calculated [by Equation (3)] albedos on a melting snow with various dust loadings. The observed data is after Adhikary et al. (1997).

uncertainty of the redistribution of particles would increase, causing deterioration in the albedo with time. In other words, the discrepancy between the calculation and observation would be widened if the ratios of dust cover were relatively small.

Secondly, it has widely been observed that the albedo of a melting snow surface, even without dust-contamination, is much lower than the albedo of the same surface prior to melting (Grenfell and Maykut, 1977; Van de wal et al., 1992; Paterson, 1994). The lower albedo of the melting surface is attributed to the trapping of a certain amount of incident total solar radiation due to multiple reflection inside cracks, ridges, channels and pores in the melting layer and absorption in the surface meltwater. For a dusted surface, reduction of albedo would be even higher apart from the effect of dust, because the surface produces more meltwater and the dust particles form pits in the surface. The combined effects of the meltwater and the pitted surface morphology on reduction of albedo would be higher compared to the bare melting surface. As the melt progresses, a number of pits would be formed, particularly on low concentration plots due to redistribution of particles. As a result, an additional effect of surface morphology on surface albedo would emerge at the latter part of the observation. However, the pits do not last long after subsequent melting, and the increased effect of the morphology would show a relative decline. The effect of surface morphology incorporated in our calculation of albedos is based on the average during the observation period that may not represent the true effect imposed by the surface morphology at the latter most part of the observation. Warren (1982) also reported that a rough surface would decrease the albedo and could impose measurement errors unless the measurement is made from a high tower to obtain a representative view of the surface.

Thirdly, our calculated albedo is based on ratios of black and white fractions measured on photos available from Adhikary et al. (1997). It is possible that we might not have detected sparsely scattered particles, particularly in the photos corresponding to less concentrated plots. However, for the plots with higher dust concentrations [P5 and P6 in Figure (6)], the calculated and observed albedo generally matches well, probably due to relatively less uncertainty about the redistribution of particles.

Because our calculation of albedo is primarily based on the ratio of dust cover, it is interesting to see the overall relationship between the dust cover ratio and the observed and calculated albedos. Figure 7 shows observed and calculated [from Equations (2) and (3)] albedos against the dust cover ratio. Unlike the albedo calculated from Equation (2) (assuming $\alpha_r = 0$), the albedo calculated by Equation (3) ($\alpha_r = 0.1$) shows a general agreement with the observed data. The agreement is better when the ratio of dust cover increases. This indicates that the surface morphology affects an additional decrease of surface albedo. In Figure 8, the observed and calculated [by Equation (3)] albedos are plotted to check the reliability of our model. There is some scatter, and the regression resulted in $y = 0.828\ x + 0.01$, where the overall correlation coefficient is 0.85. The probable sources of errors inherent in our model were discussed earlier.

In our simple calculation, the albedo of each aggregate (black fraction in the photo) is assumed to be the same as the albedo of the dust in a wet condition (0.06). This assumption seems realistic, as the aggregates were wet at the time of the measurement, and the aggregates composed mostly by overlapping of the black particles are likely to mask the optical signal from the underlying snow. The albedo of the bare part (white fractions in the photo) exposed due to the aggregation of the particles within the dusted surface is calculated as 0.5 (average) taking into account the effect of surface morphology as was also discussed earlier

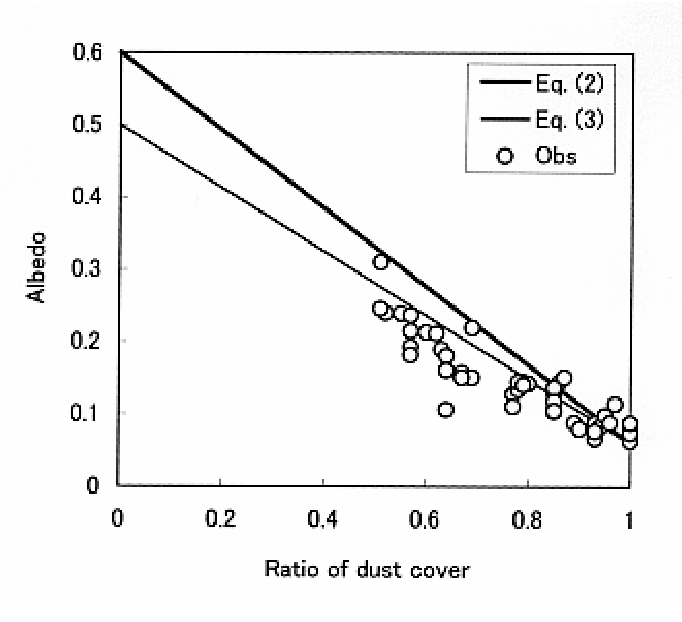

Figure 7. Albedo versus ratio of dust cover. Bold and thin lines represent calculation from Equations (2) and (3) respectively, while open circles represent the observed data.

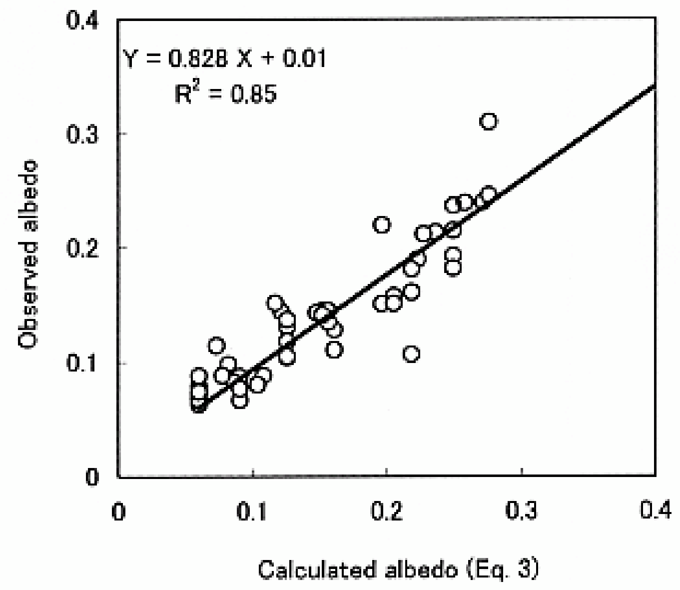

Figure 8. Relation between the observed versus calculated by [Equation (3)] albedo. The straight line represents the linear regression.

CONCLUDING REMARKS

The present study is based on limited short-term data that were obtained from small experimental plots on a seasonal snow surface. Obviously, the data are far from ideal to address long-term phenomena, say a week or more. However, this study detailed some unique aspects of the aggregation of dust particles and evolution of albedo on a flat melting snow surface. The aggregation of dust particles caused a deterioration of the relationship between initial dust concentration and surface albedo. The areal coverage of dust was decreased due to the aggregation of dust particles relative to the initial dust configuration, and as a result, the surface albedo increased dramatically. We introduced a simple method to calculate surface albedo with aggregates of dust particles. The calculated albedo compared favorably with the observed albedo when taking into account the effect of surface morphology as an additional factor to reduce the surface albedo (i.e. α_r = 0.1), apart from the effect of dust.

The present study indicates a possibility that the increase of albedo due to the aggregation of dust particles would have a similar effect as reducing the initial loading of dust concentration (by natural and/or anthropogenic sources via aeolian processes) on the surface. The reduction factors of areal coverage of dust due to the aggregation of dust particles depends on the initial loading of dust concentration. Because of the proximity to dust sources, snow and glaciers in the middle latitudes, such as mountains in the Himalayas and central Asia, are likely to be affected by the atmospherically derived dust particles mainly during the dry season (Warren and Wiscombe, 1981; Wake et al., 1994). Once melting begins, dust particles deposited on the surface possibly start to aggregate as the present study suggested. Since solar radiation is the dominant energy source in the Himalayas, aggregation of dust particles would significantly decrease the solar radiation absorption on the surface. The effect of aggregation on the surface albedo, however, would be insignificant when new snow falls and buries the contaminated surface. In closing, we might note that for any snow surface with dust input, consideration of the aggregation of dust particles and the magnitude of its effect on surface albedo changes may be important to improve surface energy balance studies for realistic prediction of the surface melting.

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REFERENCES

Adhikary, S., K. Seko, M. Nakawo, Y. Ageta, and N. Miyazaki; Effect of surface dust on snow melt, Bull. Glacier Res., 15, 85-92, 1997.

Adhikary, S., M. Nakawo, K. Seko, and B. Shakya; Dust influence on the melting process of glacier ice: experimental results from Lirung Glacier, Nepal Himalayas, IAHS AISH Publ., 264, 43-52, 2000.

Bintanja, R., S. Jonsson, and W. H. Knap; The annual cycle of the surface energy balance of Antarctic blue ice, J. Geophys. Res., 102, 1867-1881, 1997.

Chylek, P., B. Johnson, and H. Wu; Black carbon concentration in Byrd Station ice core: from 13,000 to 700 years before present, Ann. Geophysicae, 10, 625-629, 1992.

Conway, H., A. Gades, and C. F. Raymond; Albedo of dirty snow during conditions of melt, Water Resour. Res., 32 (6), 1713-1718, 1996.

Eaton, G. P.; Windborne volcanic ash; a possible index to polar wandering, J. Geol., 72 (1), 1-35, 1964.

Grebenets, V. I., and D. B. Fedoseyev; Industrial influence on glacial processes in mountains of circumpolar regions, Ann. Glacio., 16, 212-214, 1992.

Grenfell, T. C., and G. A. Maykut; The optical properties of ice and snow in the Arctic basin, J. Glaciol., 18, 445-463, 1977.

Hewitt, K.; Catastrophic landslide deposits in the Karakoram Himalaya, Science, 242, 64-67, 1988.

Higuchi, K., and A. Nagoshi; Effect of particulate matter in surface snow layers on the albedo of perennial snow patches, IAHS AISH Publ., 118, 95-97, 1977.

Knap, W. H.; Satellite-derived and ground-based measurements of the surface albedo of glaciers, Ph.D. thesis, Utrecht University, The Netherlands, 175 pp., 1997.

Kohshima, S., K. Seko, and Y. Yoshimura; Biotic acceleration of glacier melting in Yala Glacier, Langtang region, Nepal Himalaya, IAHS AISH Publ., 218, 309-316, 1993.

Kotlyakov, V. M., and L. D. Dolgushin; Possibility of artificial augmentation of melting by surface dusting of glaciers (results of Soviet investigation), IAHS AISH Publ., 107, 1421-1426, 1972.

Lliboutry, L.; Banding and volcanic ash on Patagonian glaciers, J. Glaciol., 3, 18-25, 1956.

Mattson, L. E., and J. S. Gardner; Energy exchanges and ablation rates on the debris covered Rakhiot Glacier, Pakistan, Z. Gletscherk. und Glazialgeol., 25(1), 17-32, 1989.

Oerlemans, J., and W. H. Knap; A 1 year record of global radiation and albedo in the ablation zone of Morteratschgletscher, Switzerland, J. Glaciol., 44 (147), 231-238, 1998.

Ohata, T., and K. Higuchi; Heat balance study on Glacier AX010 in Shorong Himal, east Nepal, J. Jpn. Soc. Snow Ice (Seppyo), Special Issue, 41, 42-47, 1980.

Ohata, T., K. Ikegami, and K. Higuchi; Albedo of Glacier AX 010 during the summer season in Shorong Himal, East Nepal, J. Jpn. Soc. Snow Ice (Seppyo), Special Issue, 41, 48-54, 1980.

Paterson, W. S. B.; The physics of glaciers, Pergamon press, Oxford, 480 pp., 1994.

Tegen, I., and I. Fung; Modelling of mineral dust in the atmosphere: Sources, transport, and optical thickness, J. Geophys. Res., 99, 22896-22914, 1994.

Tegen, I., A. A. Lacis, and I. Fung; The influence on climate forcing of mineral aerosols from disturbed soils, Nature, 380, 419-422, 1996.

Van de wal, R. S. W., J. Oerlemans, and J. C. Van der hage; A study of ablation variations on the tongue of Hintereisferner, Austrian Alps, J. Glaciol., 38(130), 319-324, 1992.

Wake, C. P., and P. A. Mayewski; The spatial variation of Asian dust and Marine aerosol contributions to glaciochemical signals in central Asia, IAHS AISH Publ., 218, 385-402, 1993.

Wake, C. P., P. A. Mayewski, Z. Li, J. Han, and D. Qin; Modern aeolian dust deposition in central Asia, Tellus, 46B, 220-233, 1994.

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