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Snow and firn properties and air–snow transport processes at Summit, Greenland

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Abstract

Snow–air exchange processes affect the chemistry of the atmosphere as well as the chemistry of underlying snow and firn. An understanding of the transport processes is important for quantifying and predicting changes in atmospheric chemistry and also for improving ice core interpretation. This paper focuses on the nature of diffusive and advective (ventilation) interstitial transport processes at Summit, Greenland. Field measurements of snow and firn density, permeability and microstructure are presented and compared with measurements from previous years. Density and permeability profiles follow similar general patterns from year to year; however, the specifics of the profiles show interannual variation. Field measurements of the diffusion of an inert tracer gas, SF₆, through the surface wind pack yields an SF₆ diffusion coefficient for the June 2000 surface wind pack at Summit of $\sim 0.06 \text{ cm}^2/\text{s}$; the tortuosity of the surface wind pack was 0.5. The first direct measurements of interstitial air flow in snow due to natural ventilation in undisturbed snow are presented, for light (3 m/s) winds and moderately strong (9 m/s) winds in a hoar layer 15 cm beneath the surface. The measurements during light winds showed results characteristic of diffusion profiles, while the measurements under strong winds showed evidence of ventilation. The interstitial air flow velocities are consistent with previous modeling results. Published by Elsevier Science Ltd.

Keywords: Air–snow transfer; Ventilation; Diffusion; SF₆; Permeability

1. Introduction

Processes that occur in the near-surface snow and firn affect and continuously alter the physical and chemical composition of the snow itself, and these processes also allow the snow to influence atmospheric chemistry. Summit, Greenland almost never experiences snowmelt. Chemical species found in the atmosphere become incorporated into the snow and firn, which eventually becomes compacted into glacial ice; the ice cores drilled there and at other cold glacial sites provide a record of changes in concentrations of chemical species over time. Summit was the site of a large deep ice coring effort from 1989–1993, the Greenland Ice Sheet Project 2

(GISP2), program, which retrieved a core that records $\sim 250,000$ years of climate history (e.g. Alley, 2000; Alley et al., 1997). Much has been learned from this and other ice cores; more can be learned using inverse methods for core interpretation (Waddington, 1996), if snow–air transfer processes and their impact on the underlying firn and ice are understood.

Snow–air exchange processes affect the chemistry of the atmosphere as well as the chemistry of underlying snow and firn. Recent studies have indicated that it seems likely that reactions occurring in the snow may be influencing the overall composition, oxidative state, and radical budget of the Arctic boundary layer (e.g. Sumner and Shepson, 1999; Zhou et al., 2002; Honrath et al., 1999; Peterson and Honrath, 2000). Physiochemical and photochemical processing in the snow pack occur for a variety of important chemical species. For example, carbonyl compounds that play key roles in the oxidation

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capacity of the atmosphere have recently been observed to be released to the atmosphere by the snow pack (e.g. Hutterli et al., 1999; Sumner and Shepson, 1999). NO_3^- , a member of the NO_x family of anthropogenic emissions traditionally has been assumed to be irreversibly oxidized in the atmosphere. However, recent studies at Summit and elsewhere (e.g. Dibb et al., 1998; Honrath et al., 1999; Weller et al., 1999) indicate that the snow pack is reactivating NO_3^- ; this would serve to extend its lifetime in the atmosphere. Snow is an important land surface characteristic over much of our planet and it seems plausible that its importance in assessing the chemical composition both of the atmospheric boundary layer and of the troposphere has not yet been fully appreciated. Complex processes occur in the snow on a range of scales, including diffusion of species within a snow crystal, sorption and reactions on the crystal surfaces, photochemical reactions, and interstitial diffusion and advection of air between individual crystals and through the greater snow pack. These processes must be understood before quantitative assessments of the impact of snow on atmospheric chemistry can be made.

This paper investigates the nature of diffusive and advective (ventilation) interstitial transport processes in the near-surface snow and firn at Summit, Greenland. Diffusion is the relatively slow transport process that is driven by gradients in concentration or temperature. Ventilation is interstitial air movement within the snow pack caused by “form drag” pressure variations from wind blowing over surface roughness or by pressure variations due to wind turbulence (Gjessing, 1977; Colbeck, 1989; Waddington et al., 1996). Both diffusion and ventilation affect heat and chemical species transport in the snow pack (e.g. Cunningham and Waddington, 1993; Albert, 1993; McConnell et al., 1998). Albert and McGilvary (1992) demonstrated that scalar (temperature) profiles resulting from ventilation of snow and firn arise from a balance between diffusive and advective transfer processes, and showed that there may be significant air movement in snow that temperature measurements would not reveal if steep temperature gradients or relatively high firn thermal conductivity occur.

Physical and chemical processes that occur in snow are dependent upon the physical properties of the snow and firn, which are highly layered media. Albert (1996) showed that buried high-permeability (e.g. hoar) layers can serve to channel the flow in increased lateral fluxes, and while a surface wind pack serves to decrease the flow in underlying firn, significant subsurface flow is still possible. For atmospheric chemistry, diffusion and ventilation in the top tens of centimeters of snow are important; for ice core interpretation this range extends far below. In the dry snow zone of an ice sheet, Sowers et al. (1992) describe a “convective zone” in the

uppermost layers of firn, providing an upper boundary to the diffusive layer, which would then extend from the convective zone down to the pore close-off depth, which falls at ~ 70 m depth at Summit. Therefore, a zone exists well above the pore close-off depth where there is a transition from advection to diffusion in terms of potential gas motion in the pore volume. The chemical uptake and release processes may be greatly influenced by forced air flow, the degree depending on the local interstitial velocity of the flow. This paper discusses measurements of the snow and firn properties that control the transport processes at Summit, and presents field measurements of the diffusive and advective behavior of an inert tracer gas (SF_6) in snow at Summit.

2. Snow and firn properties at Summit, Greenland

Measurements of snow stratigraphy, density, and permeability were made in a snow pit 3 m deep in June 2000. The pit was dug in a region where the snow had not been previously disturbed and the face was shaved in order to view the stratigraphy. Samples for snow density measurements were made with a 100 cc box cutter at 3 cm increments down through the pit. Permeability measurements were made with a custom permeameter that measures flow rate and pressure drop across a snow sample (Albert et al., 2000). The flow rate is varied incrementally, and only those measurements falling within the linear (Darcy) range are used to determine the permeability.

Intact samples of snow were preserved in pore filler for quantitative microscopy following the procedure of Perla (1982). The snow samples, several centimeters thick each, were carefully cut into rectangular sample containers. Chilled dimethyl phthalate was poured into free space around the edges of the sample and allowed to wick into the sample. When the sample was saturated it was then frozen for shipment back to the laboratory. At the laboratory, the samples were cut, fixed onto support plates, microtomed, and the ice crystals were allowed to sublimate. A fine-grained dark powder was then used to fill the voids where the crystals had been, the sample wiped level, and imaged using a high-resolution digital camera. A digital image-processing program, Image Processing Workbench, was used to process each image so that the original snow crystal space appears white, and the program was used to determine grain scale statistics for each sample.

The snow and firn at Summit is a layered system of wind pack interspersed with large grained and hoar layers. The hoar layers are formed in the summer (Alley, 1988; Alley et al., 1990), and by the end of summer it is common to have multiple hoar layers in the near surface. These sets of hoar layers remain identifiable as they age, indeed the visual stratigraphy of these layers as

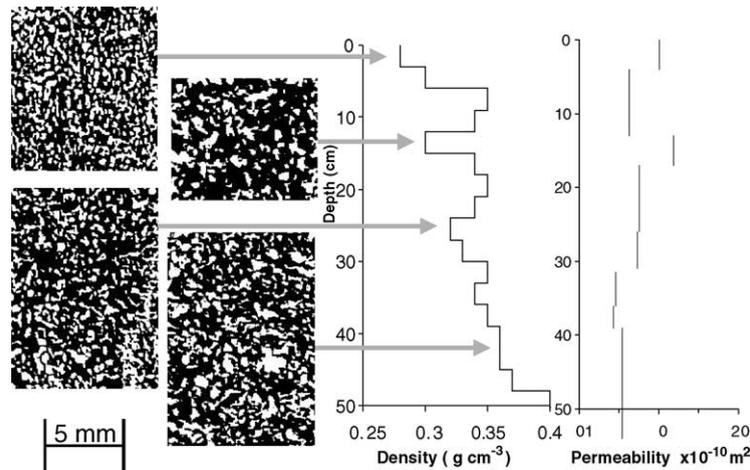


Fig. 1. Density and permeability profiles and sample microstructure images from the top 50 cm of snow and firn at Summit, Greenland in June 2000.

a summer marker is one dating technique in firn and ice core analysis through the Holocene and into the glacial transition (e.g. Alley et al., 1997; Meese et al., 1997). In Figs. 1 and 2 the density and permeability profiles are shown, along with several microstructure images, for an undisturbed site distant from all obstructions and traffic. The density profile of the top 3 m shown in Fig. 2 reveal the annual cycles in snow types; the low-density areas approximately near 70, 160, and 220 cm are the snow that was deposited in the preceding three summers; the higher-density wind pack is characteristic of winter accumulation.

Fig. 1 affords a close look at the top 50 cm of snow, a region of very active air–snow exchange. In early June 2000, except for a thin hoar layer at 12 cm depth, the top 50 cm consisted largely of layers of wind-packed snow that were deposited since the previous summer. The average density of the top 50 cm was $\sim 0.34 \text{ g/cm}^3$. Permeability is a function of the layer type and depth. Except for the windblown snow at the surface, which had a permeability of $18 \times 10^{-10} \text{ m}^2$, and the thin hoar layer at 12 cm depth, the permeability in the near-surface wind pack fell in the range of $5\text{--}9 \times 10^{-10} \text{ m}^2$. Because hoar is a very fragile crystalline structure, it was not possible to measure its permeability without the monograin sintered layers and wind pack that contained it; measurements of the combination of the hoar and several centimeters of the surrounding layers gave a net permeability of $17 \times 10^{-10} \text{ m}^2$. From hand-lens inspections of crystals in the field, typical grain sizes were 0.2 mm for the surface windblown snow, 0.25 mm for most of the wind pack in the top 50 cm, and 0.5–2.0 mm for the hoar layer near 15 cm depth.

A plot of the top 3 m of snow and firn is shown in Fig. 2. The permeability generally increases with depth in the top several meters, increasing by over an order of

magnitude from a low of $5 \times 10^{-10} \text{ m}^2$ in the surface wind pack to a range between 25 and $115 \times 10^{-10} \text{ m}^2$ between 2 and 3 m depth. The yearly swings in temperature cause temperature gradients that drive snow and firn metamorphism (Colbeck, 1989), especially in the top several meters. Metamorphic grain growth of the larger grains at the expense of the smaller grains leads to increased interstitial pore space, which leads to greater permeability in firn after first several years deposition. Between 2 and 3 m depths, the wind pack firn has grain sizes ranging from 0.25 to 1.0 mm, and the grain size of the hoar ranges between 1 and 5 mm. In the top 3 m, metamorphism clearly has a much greater impact on grain size and permeability than on density. The density clearly continues to display annual cycling at values close to their near-surface values, while the permeability shows less annual cycling and shows marked increases over the near-surface values. The wind pack crystals experience huge growth relative to the original size at deposition, while the hoar crystals, already large when they were deposited, remain large and experience some growth.

Permeability and density were also measured from pits and from a firn core at Summit several years earlier. The Summit pit and firn core permeability measurements from 1997 are shown in Fig. 3, which shows that layers of high permeability exist between ~ 2 and 6 m depth. The permeability decreases with depth below ~ 3 m due to compaction from overburden pressure, as is evident in Fig. 3. It is interesting to note that the lowest permeability layer in the top 10 m of snow and firn at Summit is the surface wind pack.

The density profile from this firn core is also plotted as a function of depth in Fig. 3. The density does depend on the layer type and depth, but it is clear that density is not a good indicator of permeability or microstructure.

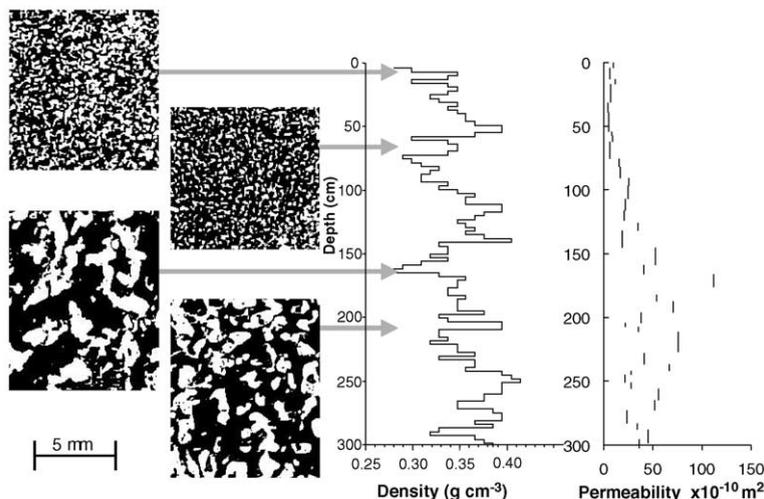


Fig. 2. Density and permeability profiles and sample microstructure from the top 3 m of snow and firn at Summit, Greenland in June 2000.

These permeability measurements suggest that the firn near the 3–5 m depth is more amenable to transport than is the shallower or deeper firn. Whether increased transport would occur there depends on the nature of the forcing; for ventilation, the nature of the surface roughness, wind, and snow permeability control interstitial air flow. The forcing conditions at Summit could drive ventilation in the top 2 m, although the firn is sufficiently permeable to allow ventilation for several meters deeper (Albert and Hawley, 2002).

While there are trends in the stratigraphy, microstructure, and permeability profiles that are recognizable in pit measurements from year to year, specifics of these profiles do have interannual variation. Permeability measurements from pit studies were made at Summit in 1994 (Albert et al., 1996) and 1995 (Albert, 1996). Those pits also show that the permeability varies according to layer type and generally falls between $2\text{--}30 \times 10^{-10} \text{ m}^2$ in the top meter of snow and firn, with generally increasing permeability below that. However, the permeability at any given depth will vary in time depending on the accumulation rate, meteorology, and the time of year that the snow is sampled. The near-surface snow and firn experience changing temperature gradients that drives metamorphosis of the crystals especially in the summer. Although snowfall at Summit occurs in all seasons (e.g. Albert and Hawley, 2000), the accumulation rate is not seasonally uniform, and in addition the temperature and wind conditions change dramatically during the year. These variations in meteorology affect the microstructure of the surface snow; hence the permeability of the surface snow and the air–snow transfer processes at Summit are also likely to be seasonally dependent.

3. Field measurements of diffusion and ventilation in the near-surface snow at Summit

Quantitative assessments of snow–air gas exchange require knowledge of the rate at which gaseous species move through the surface snow. Field experiments using an inert tracer gas, SF₆, were conducted in order to investigate processes of diffusion and ventilation in the near-surface snow at Summit under summer conditions. While diffusion is ubiquitous in nature, ventilation of the snow occurs during windy periods. To the best of our knowledge, no direct measurements of ventilation in snow exist prior to these investigations, although ventilation has been studied theoretically (e.g. Colbeck, 1989; Clarke and Waddington, 1991; Albert, 1996).

3.1. Diffusion

Using the in situ method proposed by McIntyre and Philip (1964) for soils, we measured the diffusion of SF₆ through the surface wind pack. The tests were conducted on windless days. A cylindrical sampler, closed on the top with a mixable reservoir, was pushed into the snow until the sharpened wall of the cylinder penetrated 20 cm into the snow. The stratigraphy of the snow was as shown in Fig. 1 for most of the tests, the only variation being several test sites where the hoar layer fell below 20 cm in the firn (but no discernible differences occurred in the results); the tests primarily reflect the diffusion of the gas through the surface wind pack. We injected a concentration of SF₆ into the cylinder headspace, stirred the gas in the headspace, and used syringes to withdraw air samples through a septum in the top of the cylinder at predetermined intervals during the test. The syringes

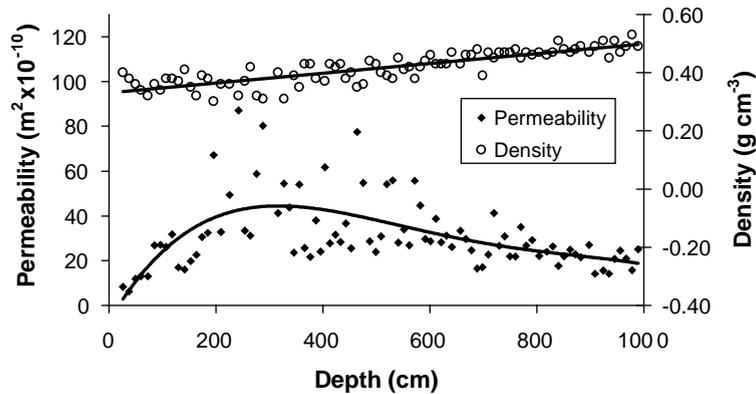


Fig. 3. Snow and firn density and permeability profile for the top 10 m at Summit, Greenland in May 1997.

were immediately sealed after withdrawal. The total collective volume of all of the samples withdrawn was <5% of the total head space of the closed cylinder. The gas samples were analyzed on site the same day using a portable gas chromatograph with a chromatograph range of 50 ppt–20 ppb. In preliminary testing using SF6 in the syringes, we found that the method of sealing the syringes successfully avoided leakage for a period of weeks. The measured decay of the SF6 in the headspace is then used to calculate the diffusion coefficient of SF6 in snow.

The diffusion coefficient of an inert gas through wind pack can be related to that in air by the following:

$$D_s = D_a \phi^m, \tag{1}$$

where D_s and D_a are the diffusion coefficients in snow and air, respectively, ϕ is the porosity of the snow, and m is determined experimentally from the diffusion measurements. D_a is taken as 0.12 cm²/s (Thibodeaux, 1996), and the porosity of the snow is calculated from the measured snow density by the following equation:

$$\phi = 1 - \frac{\rho_s}{\rho_i}. \tag{2}$$

Here, ρ is density and subscripts s and i denote snow and ice, respectively. Carslaw and Jaeger (1959) provide an analytical solution to non-steady state diffusion through a cylindrical semi-infinite porous medium:

$$C = C_0 \exp(\tau) \operatorname{erfc}(\sqrt{\tau}), \tag{3}$$

where C is the concentration of SF6 in the chamber, C_0 is the initial concentration of SF6 in the reservoir. For the conditions of this experiment, τ is given by

$$\tau = \frac{D_a \phi^{m+2} t}{z^2}, \tag{4}$$

where t is time and z is the height of the cylinder reservoir. Using the measured concentrations, snow density, and cylinder characteristics, these equations allow a single-parameter fit to Eq. (3), where m is the

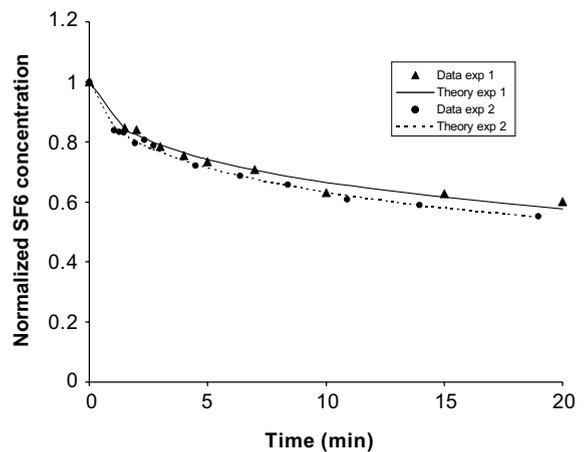


Fig. 4. Normalized concentration of SF6 as a function of time from two surface diffusion experiments. The solid line represents the best single-parameter fit to the measured concentrations, and the symbols represent the measured concentrations.

only free parameter needed to fit the measured gas concentrations to the curve. Note that Eq. (3) is valid as long as the gas diffuses down through the snow in one direction; once the SF6 “front” nears the open-ended bottom of the chamber (20 cm deep in the snow), then strictly speaking this equation no longer holds. Rolston et al. (1991) analyzed the technique and found that the experimental results appear to be valid for significantly longer times than the mathematical development would indicate. For our sampling cylinder, the mathematics indicates that Eq. (3) holds for the first 8 min. Accordingly, data from the first 8 min of the experiment were used to determine the diffusion coefficients, although we did continue to sample for longer times.

Fig. 4 shows the results of two representative experiments conducted on the surface of the wind pack at Summit in June 2000, at locations separated by ~5 m.

The symbols are measured concentrations, normalized relative to the initial concentration. A single-parameter fit of this data from the first 8 min of the experiment allows the determination of the exponent, m . The solid lines depict the curves from Eq. (3) using our experimentally determined values for m . For the June 2000 wind pack at Summit, the values we obtained for m were 1.7 and 1.3; the respective effective diffusion coefficients of SF₆ through the wind pack for the two experiments were 0.057 and 0.064 cm²/s. Other runs of the experiment on the surface wind-packed snow, conducted the same week, yielded diffusion coefficients that fell within these values. Because SF₆ is non-reactive and the pore space in the snow is much greater than the size of the molecules sampled, taking the diffusion coefficient 0.06 cm²/s for SF₆ through wind pack places an upper bound on the rate of diffusion of other chemical species measured during the 2000 Summit field campaign.

While we could not find published diffusion coefficients for wind pack at other sites, there have been several other relevant discussions on the diffusion coefficient in snow. From measurements of CO₂ efflux from seasonal snow at temperate sites, Winston et al. (1995) reported diffusion coefficients for CO₂ in snow that ranged between 0.02 and 0.3 cm²/s, but he attributed the 0.3 cm²/s to ventilation of the snow, because that value exceeds the diffusion coefficient of CO₂ in air alone. Solomon and Cerling (1987) deduced diffusion coefficients of CO₂ in snow to be 0.05 and 0.06 cm²/s. Neither set of authors described the stratigraphy of the snow pack. Apart from Winston's anomalous 0.3 cm²/s measurement, when all measurements are normalized by the diffusion coefficient of the species in air, our results are in general agreement with theirs.

These diffusion experiments described above also permit the calculation of the tortuosity of the wind pack, a parameter that frequently appears in mass and chemical transfer analysis of porous media (e.g. Dullien, 1992). The tortuosity of a porous medium expresses the degree of complexity of the pathway, and is commonly calculated as the squared ratio of the minimum possible (straight line) path length to the mean path length. Tortuosity is also commonly defined as the ratio of the diffusivity in snow to the diffusivity in air, where the diffusivity is the diffusion coefficient divided by the porosity. The tortuosity is then calculated using the following equation:

$$T = \frac{D_s}{D_a \phi}. \quad (5)$$

Using this definition we find that the tortuosity of the surface wind pack at Summit in June 2000 was ~ 0.5 .

3.2. Ventilation

While diffusion of gases in the near-surface snow is ubiquitous, under windy conditions interstitial air flow

known as ventilation occurs. In situ measurements of the movement of the inert gas, SF₆, through snow were conducted on-site at Summit in order to detect possible snow ventilation under natural forcing conditions. For these tests thin tubes were employed for injecting the source of SF₆ into the snow and for sampling the interstitial air at other locations. Each thin tube actually consisted of a small (0.3175 cm i.d.) inner steel tube, sealed at the end but with perforations in the wall of the tube very near the sealed end. This inner tube contained within a closely fitting outer tube or sleeve. The other (open) end of the sampling tube was plumbed to a short length of flexible tubing and fit with a septum to facilitate sample withdrawal. The tubes were inserted into the snow to the desired depth. The inner tube was then held in place while the outer sleeve tube was drawn up 1 cm, exposing the perforations to the snow. Three of these tube systems were inserted into the snow, 1 m apart, and in a direction parallel to the prevailing wind. Care was taken not to disturb the snow near the sampling site; a platform was set up above the snow before the start of the experiment to allow access to the samplers, and the flexible tubing was stabilized to prevent movement of the steel tubes during sampling. At the start of the experiment, 60 cc of the SF₆ concentration was injected into the center tube, and at predetermined times, 30 cc of SF₆ were withdrawn from the "upstream" and "downstream" tubes. The syringes were sealed after each sample was obtained and the gas concentration was analyzed the same day using a portable gas chromatograph.

During the period these tests were conducted, the snow surface at Summit was flat with very little surface roughness, but there were sporadic small natural snow imperfections in the snow that provided surface relief features ~ 5 cm high and were spaced ~ 10 m apart. The sampling system was placed in an area of smooth flat undisturbed snow, ~ 100 m away from the nearest building or surface obstruction. The tests were conducted over a period of several weeks and under a variety of wind speeds. At the end of each set of tests, the snow was excavated from around each tube to determine its true location in the snow layering. Data from two cases where all three tubes were in the hoar layer are presented here.

At the time of the testing, all three tubes were sampling air from a large-grained hoar layer ~ 15 cm deep in the snow. The hoar layer was ~ 4 cm thick. Fig. 5 shows the results of the tests for two wind speeds. In Fig. 5a, the winds were light (3 m/s) but steady. It can be seen that both the upstream and the downstream locations experienced the passage of SF₆ at the same rate, with the plume peaking at each site at ~ 9 min. Although the peak concentrations were different, the symmetric profile of SF₆ rise and fall at both the upstream and downstream sites suggests that the

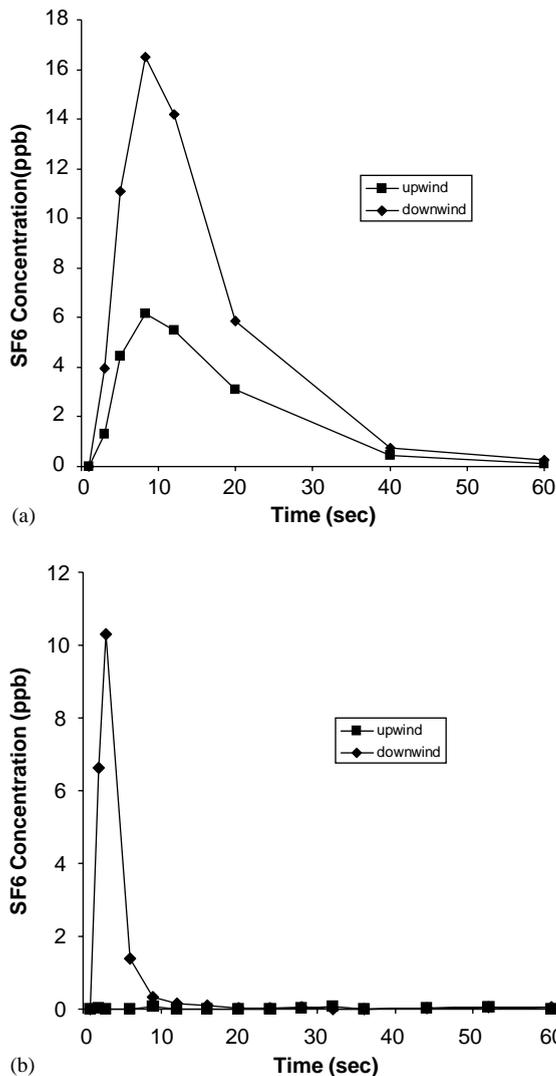


Fig. 5. In situ measurements of discrete measurements of interstitial SF6 at locations upstream and downstream of a center slug-injection site: (a) interstitial flow at 15 cm depth under ambient wind speed of 3 m/s, (b) interstitial flow at 15 cm depth under ambient wind speed of 9 m/s.

transport was dominated by diffusion. In moving from the injection tube to the sampling tube, the interstitial velocity for the peak of the SF6 plume was ~ 0.2 cm/s. This transport rate in hoar is higher than would be predicted by pure diffusion using the results of the tracer gas diffusion chamber tests presented above. However, the diffusion chamber tests were conducted in wind pack, and it might be expected that gases would diffuse more quickly through a highly permeable snow, such as hoar, than through a low-permeability snow such as wind pack, so the results are not directly comparable.

Tests were also performed at a fresh location under higher wind speeds, but still sampling the hoar layer at the same approximate depth (15 cm depth). Fig. 5b shows the results from an ambient wind speed of ~ 9 m/s. Under these conditions, there was no measurable gas detected at the upstream location, while the downstream sampling showed a rapid concentration rise and then a fall. The interstitial air flow was sufficiently high such that no gas was detected at the upstream site. This behavior is characteristic of advective transport, with the concentration “plume” moving rapidly by the sampling station. After the sampling was finished, tubes were excavated to verify that they were both sampling the same (hoar) layer, and that there were no obstructions at the perforated ends. The interstitial velocity for the peak of the SF6 plume was ~ 1.3 cm/s. Similar results were obtained in other tests when the tubes were sampled from the same layer.

It is of interest to compare these results with published results from ventilation modeling. Albert (1996) conducted two-dimensional simulations of ventilation at Summit under several conditions of surface pressure variations. The results of the advection-dominated measurements described above fall within the ranges of air flow velocities at 15 cm depth predicted in that paper. The diffusion-dominated measurements described above are lower than any of the near-surface calculated ventilation. The measured air flow rates are consistent with previously published model results.

4. Conclusions

Transport processes that occur in the near-surface snow and firn affect and continuously alter the physical and chemical composition of the snow itself, and these processes also allow the snow to influence atmospheric chemistry. Diffusion of gases into the atmosphere from the snow and into the snow from the atmosphere is ubiquitous. Wind pack is a very common snow type on ice sheets and large expanses of snow, such as Greenland and Antarctica; the diffusion coefficient for SF6 determined here may provides an upper bound on the rate that a molecule of reactive gas will move into or out of the snow in the absence of wind. Snow and firn ventilation caused by the wind is also probably ubiquitous on large expanses of snow when the wind is blowing. The depth of air flow in the snow depends on the wavelength or lateral spacing of roughness elements on the snow surface, and the intensity of the ventilation depends on the wind speed; Albert and Hawley (2002) discuss these aspects for Summit.

The properties of the snow and firn play an important role in controlling the nature and extent of the transport processes. Permeability is the key transport parameter for ventilation. The permeability of the snow and firn at

Summit varies with layer type; generally the permeability increases with depth in the top several meters, increasing by an order of magnitude from a low of $5 \times 10^{-10} \text{ m}^2$ in the surface wind pack to a range between 25 and $115 \times 10^{-10} \text{ m}^2$ near 3 m depth. The increased permeability in the firn is due to daily and seasonal swings in temperature that cause metamorphism (Colbeck, 1989), especially in the top several meters of snow and firn at Summit. Metamorphism leads to increased interstitial pore space, which yields greater permeability in the first several years after deposition. While grain growth still occurs deeper in the firn, the permeability decreases with depth below $\sim 3 \text{ m}$, due largely to compaction of the firn deeper than $\sim 3 \text{ m}$ by the overburden pressure. Permeability profiles follow the same general trend from year to year at Summit, though the specific values of the snow properties show interannual variation due primarily to variations in meteorology and accumulation. It follows that seasonal and interannual variation in the snow and firn air chemistry also may be expected.

In situ measurements of diffusion of an inert gas (SF₆) through the surface snow were presented. The diffusion coefficient of SF₆ in the wind pack at Summit in summer 2000 was $\sim 0.06 \text{ cm}^2/\text{s}$, and the tortuosity of the surface wind pack was 0.5.

SF₆ was also used to gain direct measurements of natural ventilation in undisturbed snow. Results from measurements in a hoar layer 15 cm beneath the surface showed that SF₆ concentration profiles under low (3 m/s) winds appear to be diffusion-controlled. Measurements under strong winds (9 m/s) showed evidence of ventilation. The interstitial air flow velocities are consistent with previous modeling results. Since ventilation greatly increases the rate of chemical transfer and also exposes much more of the snow depth to chemical exchange, it is important to consider the effects of ventilation on chemical exchange in snow.

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