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White on green: under-snow microbial processes and trace gas fluxes through snow, Niwot Ridge, Colorado Front Range

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Abstract The importance of snow and related cryospheric processes as an ecological factor has been recognized since at least the beginning of the twentieth century. Even today, however, many observations remain anecdotal. The research to date on cold-lands ecosystems results in scientists being unable to evaluate to what extent changes in the cryosphere will be characterized by abrupt changes in local and global biogeochemical cycles, and how these changes in seasonality may affect the rates and timing of key ecological processes. Studies of gas exchanges through snow have revealed that snow plays an important role in modulating wintertime soil biogeochemical processes, and that these can be the driving processes for gas exchange at the snow surface. Previous research has primarily focused on carbon dioxide, and resulted from episodic experiments at a number of snow-covered sites. Here we report new insights from several field sites on Niwot Ridge in the Colorado Rocky Mountains, including a dedicated snow gas flux research facility established at the 3340 m Soddie site. A novel in situ experimental system was developed at this site to continuously sample trace gases from above and within the snowpack for the duration of seasonal snow cover. The suite of chemical species investigated includes carbon dioxide, nitrous oxide, nitrogen oxides, ozone, and volatile inorganic and organic gases. Wintertime measurements have been supplemented by soil chamber experiments and eddy covariance measurements to allow assessment of the contribution of wintertime fluxes to annual biogeochemical budgets. This research has resulted in a plethora of new insight into the physics of gas transport through the snowpack, and the magnitude and the chemical and biogeochemical processes that control fluxes at the soil-snowpack and the snow-atmosphere interface. This article provides an overview of the history and evolution of this research, and highlights the findings from the ten articles that constitute this special issue.

Keywords Snow · Winter · Microbes · Respiration · Isotopes · Carbon dioxide · Nitrous oxide · Nitrogen oxides · Volatile inorganic and organic gases

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Introduction

The recognition that winter processes can make an important contribution to annual biogeochemical budgets has challenged the traditional view of winter

as a season of suppressed activity (Campbell et al. 2005). The importance of snow and related cryospheric processes as an ecological factor has been recognized since at least the beginning of the twentieth century (Chernov 1985). Even today, however, many observations remain anecdotal. Findings from this previous research on cold-lands ecosystems have been diverse and have not yet enabled scientists to evaluate to what extent changes in the cryosphere will be characterized by abrupt changes in local and global biogeochemical cycles, and how these changes in seasonality may affect the phenology and timing of key ecological processes (Marshall et al. 2008). Too often the influences of ecological processes in winter are not interpreted in the context of annual and long-term trends in nutrient budgets (Campbell et al. 2005).

Moreover, snow itself can serve as a substrate for chemical reactions. Most of this new insight is from research conducted in the polar environment. Triggered by solar irradiance, trace constituents in the snow engage in a photochemistry that causes depletion and formation of many reactive and important gas species and their exchanges with the overlying atmosphere (Grannas et al. 2007). The complexity of these reactions is challenging and much remains to be learned about the underlying processes. One of the most contrasting behaviors is seen in the polar ozone chemistry: While snow/sea-ice photochemical reactions and resulting reactant fluxes can cause complete removal of ozone in air above the snow in Arctic coastal regions within a day (Simpson et al. 2007), at South Pole, under similar irradiance conditions, emissions from the snow drive photochemical ozone production that will cause a doubling of ozone in the course of a few days (Helmig et al. 2008). In contrast to high-latitude areas, there is a paucity of research on these processes in seasonally snow-covered ecosystems in mid-latitude areas.

The omission of biological and chemical activity during the seasonally snow-covered period is due not only in part to the misconception that there is little biological or chemical activity during this period, but also to the inherent difficulties associated with winter sampling (Marchand 1996). Logistical constraints have caused data collection in seasonally snow-covered areas to generally be on a campaign basis with limited instrumentation. The problems of winter access, low air temperatures, and blowing snow cause both equipment malfunctions and problems with consistent and timely maintenance (Williams et al. 1999). Thus, while there has been progress in understanding biogeochemical processes during the snow-covered season (e.g. Groffman et al. 2001), much remains to be learned about the contribution of winter-time processes to annual biogeochemical processes in seasonally snow-covered areas.

Snow cover plays a dual role in terms of air temperature regulation (UNEP 2007). The high albedo of snow-covered areas reduces net radiation, and snow also acts as a heat sink, removing energy from the atmosphere. This means that the presence of snow cover provides effective insulation yet also inhibits soil warming until the snow melts, preventing biological activity that requires temperatures above 0°C. The low thermal conductivity of snow, however, keeps soil temperatures near 0°C throughout the winter months and thus reduces the extremes of temperature experienced by vegetation and organisms in the soil under snow.

We highlight these effects because the snowpack is in one sense a climate response and in another sense an ecological driver; for example a change in the time of disappearance of the snowpack is a threshold phenomenon that will have clear effects on species composition and biogeochemistry from local to continental scales if the change is persistent (Marshall et al. 2008). Unprecedented decreases in snow and sea-ice cover have been observed in recent years (Comiso and Parkinson 2004; Drobot et al. 2008). At low elevations and latitudes, warming leads to a change from a snow-to a rain-dominated winter precipitation regime. For example, in central Chile, air temperature data from 1975 to 2001 show an increase in elevation of the 0°C isotherm (the line on a map linking points at which the mean temperature is 0°C) by 122 m in winter and by 200 m in summer (Carrasco et al. 2005). The phenological response may be an earlier commencement, for example, of photosynthesis and transpiration by plants (Monson et al. 2006a), which could in turn result in a decrease in soil moisture earlier in the summer during the time when vegetation may be stressed due to high net radiation, high air temperatures, and low humidity. An earlier snowpack disappearance would also eliminate the insulation that prevents soils from freezing during winter cold snaps, which might modify plant and microbial metabolism and perhaps distributions (Groffman et al. 2001).

Air temperatures in arctic Alaska have increased 0.5°C per decade for the past 30 years, with most of the warming coming in winter (e.g. Hinzman et al. 2005). Over the same period, shrub abundance has increased, perhaps a harbinger of a conversion of tundra to shrubland (e.g. Tape et al. 2006). Evidence suggests that winter biological processes are contributing to this conversion through a positive feedback that involves the snow-holding capacity of shrubs, the insulating properties of snow, and hardy microbes that can maintain metabolic activity at temperatures of −6°C or lower. Increasing shrub abundance leads to deeper snow, which promotes higher winter soil temperatures, greater microbial activity, and more plant-available nitrogen (Sturm et al. 2005).

For example, in forest ecosystems in cold climates, the mineralization of soil organic matter during the winter can potentially occur at high rates (Groffman et al. 2001; Wickland et al. 2001; Brooks et al. 2005; Hubbard et al. 2005; Monson et al. 2005, 2006a, b). The efflux of CO_2 from soils to the atmosphere continues throughout the winter with recent measurements indicating that 60% or more of growing season carbon uptake can be lost during the winter (Sommerfeld et al. 1993; Winston et al. 1995; Monson et al. 2002). These data unanimously point towards significant carbon loss from wintertime, subnivial respiration that needs to be considered in evaluating the ecosystem annual carbon exchange (Monson et al. 2006b; Maljanen et al. 2007; Nobrega and Grogan 2007). We need an improved understanding of how these fluxes may change in response to changing snow properties such as depth, density, and duration.

In contrast to the studies that have examined snowpack CO_2 fluxes, comparatively little attention has been given to other snow trace gas fluxes, in particular to nitrogen gas species. Oxidized nitrogen inputs from precipitation have significantly increased over the past century (Galloway et al. 2008), and enhancements of nitrate in atmospheric deposition have been reported in most environmental compartments, including precipitated snow (Williams and Tonnessen 2000). As the CO_2 flux studies have provided convincing evidence for an active, wintertime respiration processes in the soil underneath the snow, it is likely that similar nitrogen cycling occurs. However, subnivial nitrification processes, i.e. production of nitrogen oxides ($NO + NO_2 = NOx$) and its snowpack fluxes have not received this attention. Most likely, this neglect is due to the fact that while stable gases (CO_2, CH_4) can be investigated by sample collection in the field with subsequent laboratory analysis, NOx flux experiments require more sophisticated, in situ analytical tools that are more difficult to deploy outside at snow-covered field sites.

New influences of snow in the environment continue to be discovered and the plethora of new research conducted during recent years has slowly eroded the picture of snow as being solely an inert substrate. More and more "Shades of White" are now emerging, pointing towards important roles of snow in the environment. It is becoming increasingly evident that the snow is a complicated medium, and that influence of snow on chemical and biological exchanges is highly variable and dependent on climatic conditions and geographic location.

Microbial and trace gas flux studies at Niwot Ridge: a review of previous studies

Research activity at Niwot Ridge in the Colorado Front Range (Fig. 1) has been in the vanguard of biogeochemical cycling during the winter season for most of the last two decades. Brooks et al. (1996) built on the pioneer work of Sommerfeld et al. (1993) to show that CO_2 flux through the winter snowpack in an alpine environment was correlated with microbial activity. The Brooks et al. (1996) paper was followed by other reports investigating microbial activity under the snowpack and resulting fluxes of trace gas through snow (Brooks et al. 1997, 1998; Brooks and Williams 1999; Ley et al. 2004; Lipson et al. 1999, 2000, 2001; Williams et al. 1996, 1998). Schadt et al. (2003) used microbiological and molecular techniques to elucidate the phylogenetic composition of undersnow microbial communities at Niwot Ridge and showed that tundra soil microbial biomass reaches its annual peak under snow, and that fungi account for most of the biomass. Phylogenetic analysis of tundra soil fungi revealed a high diversity of fungi and three novel clades that constitute major new groups of fungi (divergent at the subphylum or class level). These scientific reports substantially broaden our understanding of both the diversity and biogeochemical functioning of microbes in cold environments.

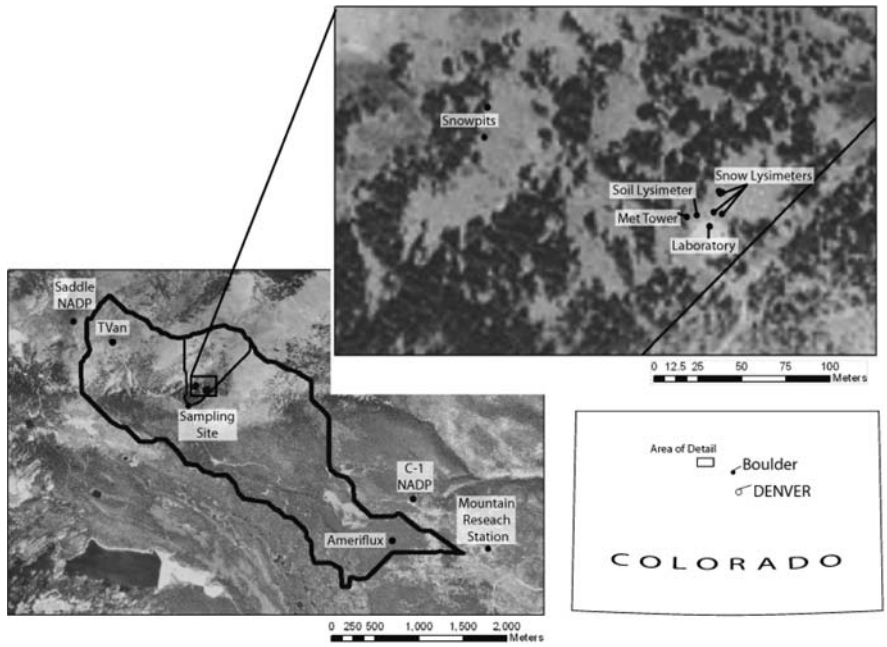

Fig. 1 Location and site map of C1, T-Van, and Soddie sites, Niwot Ridge, Colorado. Also shown are NADP sites. Sampling sites at the Soddie (enlarged area) are shown for the meteorological station, snow, snow melt, soil lysimeters, and surface waters. Delineations indicate the Como Creek watershed and the headwater basin boundaries

The NWT snow research facilities

In this special issue we report on new advances in snow experiments from three sites on Niwot Ridge. Snow studies at these facilities have provided the opportunity to increase our understanding of the biogeochemical functioning of microbes in cold environments and how that activity influences the export of trace gases through a seasonal snowpack.

An above-canopy eddy covariance site was established in the subalpine forest of Niwot Ridge as part of the AmeriFlux network (Monson et al. 2002; Turnipseed et al. 2002). This site near C1, is located at an elevation of 3050 m approximately 8 km east of the continental divide (Fig. 1). A programmable, portable, trace gas measuring system was installed at the site in 2003 that allowed in situ and continuous measurements of CO_2 concentrations in and above the snowpack (Burns et al. 2004). Continuous measurements of CO_2 flux using the eddy covariance approach showed that the amount of respired carbon lost during the winter can be as much as 90% of the carbon gained the previous summer (Monson et al. 2005), while measurements of CO_2 flux simultaneously above the canopy and through the snowpack shows that 35–48% of the total wintertime ecosystem respiration was by soil respiration emitted through the overlying snowpack (Monson et al. 2006b) and that winter soil respiration under the snowpack was controlled by soil temperature and microbial activity (Monson et al. 2006a).

A second facility was developed in a forest clearing near tree line at the high-elevation Soddie site (3340 m). This site has an underground laboratory 3 × 9 × 2 m in size, line power, with an array of snow lysimeters, and zero-tension soil lysimeters (Fig. 1). Adjacent to the soil lysimeters is a suite of meteorological instruments. Snowpits are sampled weekly for physical and chemical parameters ~100 m from this experimental site (Fig. 1) so as not to disturb the natural snowcover over the snow and soil lysimeters. This high-elevation meadow is bounded by ribbon forest that is a mixture of spruce (*Picea engelmannii*) and fir (*Abies lasiocarpa*), with some limber pine (*Pinus flexilis*).

Studies of trace gas flux through the seasonal snowpack at the Soddie site began in the 2003–2004 winter season (from here on referred to as winter 2004) to investigate ozone production and loss during the winter, and have continued with more and expanded gas measurements in each season (Table 1). This research builds upon a new snow gas sampling system (snow tower), that allows for the continuous withdrawal of air from multiple gas inlets inside the snowpack. Analytical instrumentation has been fully automated and is accessible and

Table 1 History of snowpack studies conducted using the snowpack trace gas sampling tower

Winter season	Sampling tower	Gases measured	Other comments
2003–2004	5 Inlet heights	O_3	First deployment of snowpack tower at Soddie (3345 m asl) site. Results published by Bocquet et al. (2008).
2004–2005	5 + 3 Inlet heights	O_3, CO_2, NO*x*, VOC	Second Soddie deployment, installed second tower over Tedlar-covered area; ~bi-weekly snow chamber flux experiments (O_3, CO_2, NO*x*); hosted photochemical experiment during March 2005, where whole air flask samples for volatile inorganic and organic gases were collected.
	5 Inlet heights	O_3	Deployment of second tower at the Niwot Ridge Tundra Lab (3528 m asl).
2005–2006	5 + 3 Inlet heights	O_3, CO_2, NO*x*, N_2O	Third Soddie deployment; repeated Tedlar-covered experiment with improved side-wall covers. Conducted summertime CO_2 and N_2O chamber flux experiments.
2006–2007	8 + 3 Inlet heights	O_3, CO_2, NO*x*, N2O	Fourth Soddie deployment; repeated Teflon-covered experiment with better materials and installation technique; added differential pressure measurements; added soil water content measurements; improved snow chamber flux experiments (ozone, CO_2, NO*x*, N_2O); summertime flux chamber experiments (CO_2, N_2O).
2007–2008	8 Inlet heights	8 Inlet heights	Fifth Soddie deployment, started regular whole air flask sampling with programmable flask sampling package (PFP).
	5 + 3 inlet heights	O_3, CO_2, NO*x*	Comparison study with a low elevation, below-canopy site at the University of Michigan Biological Station (UMBS), Michigan; second tower over adjacent Tedlar-covered area.

controllable remotely via a network connection, thus allowing operation and close supervision without presence at the site. For the 2005–2006 season (from here on as winter 2006), a second, adjacent tower was installed in an area where the soil surface was covered with a light-transparent Tedlar® sheet. This experiment suppressed the soil-snow gas exchange and facilitated experiments to differentiate within-snow chemical processes from soil-snow exchanges.

The third study site utilized in this snow research is the alpine T-Van site, at an elevation of 3523 m above sea level, ~1 km in distance from the Soddie site. At T-Van weekly samples for determination of ambient air concentration of CO_2 have been collected by the Global Monitoring Division of NOAA, Boulder, CO, since 1968. This record of ambient CO_2 is the longest North American record of atmospheric CO_2 concentrations and the third longest in the world (Bowman and Seastedt 2001). The desire for above-treeline CO_2 flux measurements through the seasonal snowpack motivated the installation of an eddy covariance flux system adjacent to T-van. To our knowledge, this is the highest-elevation eddy covariance site in the world, exceeding the elevation of flux measurements made on the Tibetan Plateau (3,250 m; Gu et al. 2008).

New findings presented in the special issue

Schmidt et al. (snow molds; Ameriflux C1 site)

The biogeochemical studies in seasonally snow-covered environments just described indicate that microbial activity under late winter snows can contribute significantly to fluxes of greenhouse gases and to cycling of nitrogen and carbon (Brooks et al. 1998; Larsen et al. 2007; Lipson et al. 1999; Campbell et al. 2005; Schmidt and Lipson 2004; Monson et al. 2006a). Schmidt et al. (2008a, b) have argued that saprotrophic snow molds are a major component of the subnivean environment and play an important and previously overlooked role in nutrient cycling and gas fluxes in seasonally snow-covered environments. Snow molds are especially prominent in sub-alpine forests of the Colorado Front Range (Rocky Mountains) where they form dense mycelial mats under late season snow packs. These fungal communities are ephemeral in nature and rapidly disappear once the snow is gone.

The paper by Schmidt et al. (2009) shows that "snow molds" exhibit robust exponential growth at temperatures from −3.0 to −0.3°C. Secondly, they show that Q_{10} values based on growth rates across the temperature range of −2.0 to −0.3°C for these vary from 22 to 330. Last, they suggest that with only moderate snow mold growth (several generations), the combined sensitivities of growth and metabolism to small changes in beneath-snow soil temperature create a double exponential in the Q_{10} function that may explain the extremely high ($\approx 1 \times 10^6$) Q_{10} values observed in past studies (e.g. Monson et al. 2006a).

Lipson et al. (microbial respiration; Ameriflux C1 site)

It is likely that soil microbial respiration is highly sensitive to the unique physiological characteristics of soil microbial communities. It has been observed that there is an inevitable thermodynamic trade-off between growth rate and yield among heterotrophic organisms (Pfeiffer et al. 2001). Past authors have proposed that two opposing ecological strategies exist at either end of this spectrum: a fast growing, low yield competitive strategy and a slow-growing, high yield cooperative strategy (Kreft and Bonhoeffer 2005; Pfeiffer et al. 2001). The theoretical relationship between biomass-specific respiration rates and growth kinetics suggests a principle for understanding how physiological properties of microbial communities can scale up to shape ecosystem respiration.

To address this issue, Lipson et al. (2009) conducted a series of soil respiration experiments to test whether growth kinetics of the microbial community vary seasonally, particularly between snow-covered versus summer conditions, and whether there is a consistent negative relationship between growth rate and yield. They found that soil microbial communities from underneath the snow had higher growth rates and lower growth yields than the summer and fall communities from exposed soils, causing higher biomass-specific respiration rates. Growth rate and yield were strongly negatively correlated. Based on experiments using specific growth inhibitors, they report that bacteria had higher growth rates and lower yields than fungi, overall, suggesting a more important role for bacteria in determining soil heterotropic respiration. Under the most realistic scenario using seasonally changing communities, they estimated soil heterotrophic respiration at 232 mol m^{-2} $year^{-1}$, or 47% of annual total ecosystem respiration for this forest.

Bowling et al. ($\delta^{13}C$ of winter respiration; Ameriflux C1 site)

Another technique to evaluate whole-forest respiration is to measure the carbon isotopes of CO_2 (see review by Bowling et al. 2008). Most of our understanding of the isotopic composition of whole-forest respiration (commonly called δ_R or $\delta^{13}C_R$) in temperate regions comes from research conducted in the warmer summer months (Alstad et al. 2007; Bowling et al. 2002; Hemming et al. 2005; Knohl et al. 2005; Lai et al. 2005; McDowell et al. 2004; Mortazavi et al. 2005; Ponton et al. 2006), and there is little isotopic understanding of winter processes. Bowling et al. (2009) conducted a field study in the C-1 subalpine forest in winter to address two objectives: (1) quantify the isotopic composition of soil respiration in winter and evaluate potential biological controls on the $\delta^{13}C$ of winter respiration; and (2) examine the $\delta^{13}C$ content of CO_2 in the snowpack in the context of diffusive and advective transport. They found that under-snow CO_2 mole fractions were observed up to 3, 500 μmol mol^{-1}, and $\delta^{13}C$ of CO_2 varied from ∼ −22 to ∼ −8‰. The $\delta^{13}C$ of soil respiration calculated from mixing relationships was −26 to −24‰, and although it varied in time, it was generally close to that of the bulk organic horizon (−26.0‰). There was clear evidence of isotopic enrichment associated with diffusive transport as predicted by theory, but simple diffusive enrichment (4.4‰) was not observed. Instead, ventilation of the snowpack by sustained wind events in the forest canopy led to changes in the diffusively enriched gas profile. There were highly significant correlations between the apparent isotopic content of respiration from the soil with wind speed and pressure. In summary, physical factors influencing gas transport substantially modified and potentially obscured biological factors in their effects on $\delta^{13}C$ of CO_2 within this subalpine forest snowpack.

Blanken et al. (CO_2 eddy covariance; alpine T-van site)

Continuous measurements of water and CO_2 fluxes until now have not been measured continuously in the

alpine tundra. Blanken et al. (2009) present direct observations of water and CO_2 exchange above high-altitude alpine tundra near the T-Van site. Likely these are the highest-elevation eddy covariance flux measurements ever reported. They compare and contrast the alpine measurements conducted over the adjacent subalpine forest at C1, over a period spanning two summers and one winter. Energy balance closure at the alpine site averaged 71% during the winter and 91% during the summer, similar to the subalpine site at C1. The period of net CO_2 uptake (negative *NEE*) was 100 days at the alpine site with a net uptake of 16 g C m^{-2}, compared to 208 days at the forest site with a net uptake of 108 g C m^{-2}, with initiation of net uptake coinciding with air temperatures reaching +10°C at both sites. Winter respiration losses at the alpine site was 164 g C m^{-2} over 271 days, compared to 52 g C m^{-2} over 175 days at the forest site, with the initiation of net loss coinciding with air temperatures reaching −10°C at each site. Blanken et al. (2009) show that with suitable site selection and experimental design, eddy covariance techniques can be used to make reliable measurements of surface–atmosphere interactions at a high-elevation alpine tundra site situated in complex terrain.

Williams et al. (snow and water chemistry; Soddie site)

Snowpacks can accumulate significant amounts of particulates and solutes from atmospheric deposition (Williams and Melack 1991a). The rapid release of water and solutes from the seasonal snowpack has the potential to exert a significant impact on terrestrial and aquatic ecosystems (Williams and Melack 1991b; Williams et al. 1996; Lepori et al. 2003; Edwards et al. 2007). Williams et al. (2009) report on the storage and release of both inorganic and organic solutes to the soils underneath the snowpack, and subsequent effects on the chemical and nutrient content of the underlying soil solution and the adjacent headwater stream. The concentration of inorganic nitrogen (N) stored in the seasonal snowpack at the Soddie site of ~11 μeq L^{-1} was on the upper end of values reported for the northern hemisphere when compared to most areas of the Alps, Himalayas, and Tien Shan mountain ranges, and consistent with other reports of snowpacks in the Rocky Mountains. The storage of inorganic N in the snowpack at maximum accumulation averaged about 2 kg N ha^{-1}. Solutes were released from storage in the form of an ionic pulse, with a maximum concentration factor of about four. In contrast to the seasonal snowpack, the dominant form of N in the soil solution was dissolved organic N. Thus, soils underlying the seasonal snowpack appear to assimilate inorganic N released from storage in the snowpack and convert it to organic N. A two component mixing model suggests that the majority of streamflow was this year's snowmelt that had infiltrated the subsurface and undergone subsequent biological and geochemical reactions. The inorganic N in surface waters at the headwaters of Como Creek was always near or below detection limits, suggesting that this area at treeline is still N-limited.

Seok et al. (physical controls on CO_2 flux through snow; Soddie site)

The diffusion method (DM) is generally used to calculate the fluxes of trace gases through the seasonal snowpack. The DM relies on the assumption that gas transfer inside the snowpack is determined by molecular diffusion. However, there are other factors such as pressure-related phenomena that influence gas exchange from the soil through any permeable medium (in particular, snow) to the atmosphere (Massman 2006). A number of studies (Massman et al. 1997; Jones et al. 1999; Hubbard et al. 2005; Takagi et al. 2005; Suzuki et al. 2006) have pointed out the large potential error that may occur when the DM approach is applied to trace gas flux through the snowpack because of the effects of advection or wind-pumping. However, quantitative descriptions and corrections of this effect on the flux remain highly uncertain.

Seok et al. (2009) developed and deployed a new system for sampling trace gas fluxes through the seasonal snowpack at the Soddie site. The sampling manifold was in place throughout the entire snow-covered season, allowing for continuous air sampling with minimal disturbance to the snowpack. They sampled at eight heights in and above the snowpack about hourly for various trace gases, and evaluated the DM using CO_2 data. Various vertical concentration gradients were determined from the multiple height measurements, which allowed calculation of

vertical gas fluxes through the snowpack using Fick's first law of diffusion. Comparison of flux results obtained from different height inlet combinations show that under most conditions fluxes derived from individual gradient intervals agree with the overall median of all data within a factor of 1.5. Measured differential pressure amplitude exhibited a linear relationship with wind speed, suggesting that wind speed is a sound proxy for assessing advection. The neglect of this wind-pumping effect resulted in considerable underestimation of gas fluxes. From an analysis of dependency of fluxes on wind speeds during a 3 week period in mid-winter, they determined that over this period actual gas fluxes were 57% higher than fluxes calculated by the diffusion method, which omits this dependency.

Liptzin et al. (CO_2 ecosystem controls; Soddie site)

Using the approach of Seok et al. (2009), Liptzin et al. (2009) quantified CO_2 fluxes through the snowpack with the gradient method in winter 2006 and 2007 and with chamber measurements during summer 2007. CO_2 flux results of 0.71 μmol m^{-2} s^{-1} in 2006, and 0.86 μmol m^{-2} s^{-1} in 2007 were among the highest reported for snow-covered environments in the literature. These fluxes resulted in 156 and 189 g C m^{-2} emitted over the winter, ~30% of the annual soil CO_2 efflux. In general, the CO_2 flux increased during the winter as soil moisture increased. They developed a conceptual model with distinct snow cover zones to describe this as well as the other reported temporal patterns in CO_2 flux from seasonally snow-covered soils. As snow depth and duration increase, the temporal pattern in CO_2 flux changes from pulses of CO_2 associated with freeze-thaw events (zone I), to the lowest CO_2 fluxes and temperatures co-occurring in mid-winter (zone II), to CO_2 fluxes increasing gradually with soil moisture under the snowpack such as in the current study (zone III), to CO_2 fluxes decreasing as available carbon is consumed (zone IV). The factor controlling the CO_2 flux shifts from freeze-thaw cycles (zone I) to soil temperature (zone II) to soil moisture (zone III) to carbon availability (zone IV). This model predicts that interannual variability in snow cover or directional shifts in climate may result in dramatically different seasonal patterns of CO_2 flux from seasonally snow-covered soils.

Helmig et al. (NO*x*; Soddie site)

Emissions of nitrogen oxides from soil constitute a main input of reactive oxidized nitrogen into the atmosphere. Soil NO fluxes have been studied for a long time; findings from this research emphasize the wide dynamic range of emission rates, and the complexity of their controls (Ludwig et al. 2001). It was a big surprise, when ~10 years ago two studies conducted on the Greenland ice sheet (Honrath et al. 1999) and in coastal Antarctica (Jones et al. 2000) (Jones et al. 2001) reported NO being released from sunlit snow. Follow-up research in seasonal snow collected in Northern Michigan (Honrath et al. 2000) suggested that similarly NO may be produced and released from mid-latitude snow. Helmig et al. (2009a) at the Soddie site showed enhanced ($NO + NO_2$) levels in the snow, with interstitial air concentrations at times exceeding ambient air levels (above the snow surface) by a factor of 10–50. But, in contrast to the polar findings, the primary source of NO at NWT was found to be emissions from the underlying soil, and there was no evidence of NO being formed by photochemical reactions in the snow, though any such signal would likely have been masked by the high concentrations from the soil emissions. The determined mean flux value of 0.005–0.008 nmol m^{-2} s^{-1} puts the NWT NO flux in a similar range as fluxes reported in the polar literature. This research is the first work showing the consistent, all-winter long release of ($NO + NO_2$) from a mid-latidute snowpack. Given the importance of $NO + NO_2$ in atmospheric oxidation chemistry, in particular in ozone cycling, findings from this work have important implications for tropospheric chemistry over snow and warrant further research in this area to better constrain these fluxes, their controls, and dependency on ecosystem parameterizations.

Filippa et al. (seasonal and annual N_2O fluxes, Soddie site)

While a substantial amount of research has been conducted on wintertime CO_2 respiration fluxes, emissions of oxidized N gases have been poorly assessed, in particular concerning mountain ecosystems. Brooks et al. (1997) conducted one of the few reported studies, at the NWT alpine tundra site. Their work on N_2O revealed substantial concentration

enhancements in air samples collected from the snowpack. The more than 1,250 individual gas measurements reported in Filippa et al. (2009) show extensive N_2O enrichment in the NWT snowpack, with peak concentrations reaching ~3 times ambient levels. This is by far most extensive data set obtained from N_2O snowpack measurements reported to date. Incorporating the snowpack gradient data into the diffusion model yielded a mean wintertime flux estimate of 0.05–0.07 nmol m^{-2} s^{-1} for this high alpine ecosystem. These fluxes were ~10 times higher than the determined ($NO + NO_2$) flux, indicating that N_2O is the primary oxidized nitrogen species released in the winter. N_2O fluxes during the snow-free season declined as the soil dried out during the summer, albeit this general tendency was disrupted by N_2O bursts following precipitation events. The integrated summer N loss, at 1.1–2.4 kg N ha^{-1} was ~5–8 times higher than the total flux calculated for the winter.

Helmig et al. (VOC; Soddie site)

During a short, 10-day intensive sampling campaign in winter 2005, a number of visiting researchers utilized the Soddie facilities for snowpack experiments and preparation/testing of their instrumentation before deployment at Summit, Greenland. More than 50 volatile gases were determined by gas chromatography in whole air flask samples collected from the two snow sampling towers. Results from these measurements reported in Helmig et al. (2009a) clearly show how the NWT snowpack functions as a source of trace gas species, and the release rates for $CHCl_3$, dimethylsulfide, CS_2, and $CHCl_3$ add four more compounds to the list of gas emissions that previously have been reported from snow-covered ecosystems. The complexity of the snowpack behavior is exemplified by the fact that for 19 other gases uptake to the snow was observed. The snowpack being a sink for these gases has implications for their atmospheric budgets. Of particular interest is the uptake of climate forcing species, i.e. methane and ozone precursor compounds (volatile organic compounds), as accurate description of sources and sinks of these gases are of importance for improvement of climate models and their predictive capabilities. A second group of compounds that warrants attention are halogenated species. Here, a total of 13 gases were identified to be removed by the snowpack. Several of these species are among the group of persistent chlorofluorocarbons (CFC) and hydrochlorofuorocarbons (HCFC) that determine the stratospheric halogen burden and ozone depletion chemistry. The discovery of this new sink for these gases raises the question about the magnitude of the global snow and soil sink of these compounds, and if a better quantitative description of this loss would improve atmospheric budget assessment of these gases, their atmospheric lifetime estimates, and predictions of the time scale of the stratospheric ozone hole recovery.

Synopsis and outlook

The new research presented in the contributions to this special issue represents a major stride forward in the experimental methodologies and their characterization for snowpack gas flux research. This research also delivers a wealth of new insight into the magnitude and controls of gas fluxes, including descriptions of many gas species that hitherto had not been investigated for their wintertime snow fluxes. These findings re-emphasize the high microbial activity present in subniveal snow in this high alpine ecosystem, and its many influences on trace gas levels and fluxes through the snowpack. There are important new questions that arise from the insights that were gained so far. How particular are biogeochemical processes in these soils of the Colorado Front Range? In particular, what controls the emission of CO_2 from soils under the seasonal snowpack? Are findings from the NWT site applicable to lower elevation sites? What is the influence of the length of the snow-covered period on these gas fluxes? How important are snow fluxes to atmospheric gas fluxes, burden, and chemistry? An important caveat to the results presented here is that all the trace gas measurements are at a point in space. An outstanding question is how does the flux of trace gases vary in space?

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