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The Penetration of Solar Radiation into Granular Carbon Dioxide and Water Ices of Varying Grain Sizes on Mars

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Key Points:

- 1) The penetration depth of broad spectrum solar irradiation is greater in carbon dioxide ice than in water ice
- 2) Penetration depth varies with grain size in a predictable manner which has been modelled
- 3) The difference in penetration depth between water and carbon dioxide ices increases with grainsize

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Abstract

The penetration depth of broad spectrum solar irradiation over the wavelength range 300 nm – 1100 nm has been experimentally measured for water and carbon dioxide ices of different grain size ranges. Both of these ice compositions are found on the surface of Mars, and have been observed as surface frosts, snow deposits and ice sheets. The e-folding scale of snow and slab ice has been previously measured, but understanding the behaviour between these end-member states is important for modelling the thermal behaviour and surface processes associated with ice deposits on Mars, such as grain growth and slab formation via sintering, and carbon dioxide jetting leading to the formation of araneiforms. We find the penetration depth increases in a predictable way with grain size, and an empirical model is given to fit this data, varying with both ice composition and grain size.

Plain Language Summary

Most water on Mars exists as ice - on the polar caps and in the subsurface, like permafrost on Earth. Temperatures fall low enough for carbon dioxide to also freeze. Carbon dioxide is the main constituent of Mars' seasonal polar caps. During spring, the increased sunlight and warmer temperatures can cause the ice sheets to break up, forming granular ice deposits. We have measured the amount of sunlight transmitted through samples of water and carbon dioxide ice. We previously made similar measurements in solid water and carbon dioxide ice and snow samples. Our new measurements look at the grain sizes in-between. When combined, they can be used to calculate the penetration depth of sunlight in a variety of ice deposits based on composition and grain size. Understanding this process is important because solar radiation can cause warming within and sometimes below the ice. This 'Solid-State Greenhouse Effect' is responsible for the unique ice-related features seen on the surface of Mars.

1. Introduction

Previous studies have reported the penetration depth of broad-spectrum solar irradiation in CO₂ ice in its most massive form [Chinnery *et al.*, 2018] and at its finest - CO₂ snow [Chinnery *et al.*, 2019], but how do these two measurements relate to each other, and what is the behaviour exhibited in between these two end-members? Is this same behaviour also seen for water ice? Measurements of light penetration in water ices have been undertaken in the past, but these have used naturally occurring Antarctic snow and sea ice with all associated contaminants [e.g. Beaglehole *et al.*, 1998; Brandt and Warren, 1993; Datt *et al.*, 2015; Perovich, 1996], impure snow [Kaufmann and Hagermann, 2015], or the measurements were made using narrower wavelength ranges, such as France *et al.* [2010]. Fewer previous works have investigated light penetration in CO₂ ice, but those published have also suffered from contaminants [Egan and Spagnolo, 1969] and used samples of only micrometre to several millimetres in size [Hudgins *et al.*, 1993; Quirico and Schmitt, 1997]. What has not been addressed is the relationship between the broad-spectrum penetration depth of solar radiation and ice grain size. The penetration depth, or e-folding scale, is defined as the depth of required to reduce the intensity of incident light to 1/e (~37%), of its initial intensity. It is an important but currently poorly constrained control on the extent of a 'Solid-State Greenhouse Effect' (SSGE) induced in a surface ice deposit [Möhlmann, 2010].

In this paper we present our findings on how the e-folding scale varies with grain size for both water and carbon dioxide ices. This has significant implications for understanding the evolution of the Martian seasonal and permanent polar caps, which incorporate both ice compositions in varying proportions over a wide range of grain sizes, which vary with time. It is important to understand how light penetrates into ice in all its different forms, as this leads to unique surface processes, such as CO₂ jetting [Kieffer *et al.*, 2006]. Having constraints for the e-folding scale for the full range of ice grains sizes and compositions will lead to improved models and a greater understanding of the Martian surface.

1.1 Background

The Martian atmosphere consists of ~95% CO₂ and just 0.03% H₂O vapour [Gillmann *et al.*, 2009]. However, vast quantities of water ice are sequestered in the 1 km thick northern polar residual cap, the southern polar residual cap (SPRC) and in the subsurface. CO₂ ice forms a ~10m thick layer overlying the water ice on the SPRC. 12% - 16% of the mass of the atmosphere deposits each winter to form the seasonal CO₂ ice sheets [Genova *et al.*, 2016], reaching a maximum thickness of 1.5 m in the north, and ~1 m in the south [Matsuo and Heki, 2009; Smith *et al.*, 2001], although other estimates suggest up to 2 m in places [Aharonson, 2004].

Seasonal ice cap growth begins in autumn, which is thought to occur via a combination of direct deposition of CO₂ from the atmosphere to the surface, and precipitation of CO₂ snow [Kuroda *et al.*, 2013]. For the purposes of this investigation, “snow” is used to describe fine-grained (≤ 1 mm) deposits of either water or CO₂ ice. Based on observations by the Mars Climate Sounder (MCS), Hayne *et al.* [2014] developed a model which suggests CO₂ snowfall contributes 3% - 20% of ice mass to the southern seasonal ice deposits at 70° to 90°S latitudes. There is likely to be very little water snow fall due to the presence of only a few precipitable micrometres (1 pr- μm 1 gm⁻²) in the atmosphere at any one time [Spiga *et al.*, 2017], although the Phoenix Lander observed very fine layer (μms) of water frost forming overnight [Smith *et al.*, 2009]. CO₂ ice which initially forms as snow and frost gradually sinters and anneals to form slab ice with high transparency and low albedo [Forget, 1998; Forget *et al.*, 1995; Forget and Pollack, 1996]. The sintering process causes grain growth and densification over time, and so the penetration depth of that ice deposit will increase as the ice becomes more translucent.

Mason and Brown [1989] first described the Solid-State Greenhouse Effect (SSGE) as the process by which subsurface heating occurs via sunlight penetrating through translucent media. Specifically, it occurs when ices are present on a planetary surface, which are translucent in the visible light range, but opaque in the infrared. This allows radiation to penetrate through the surface of the ice, but inhibits the re-radiation of infrared energy, often leading to the temperature maxima being located below the surface of the ice.

1.2 Ice-related Processes and Features

The concept of the SSGE forms the basis of the CO₂ jetting model, or Kieffer model, describing the formation mechanism of ‘spiders’ [Kieffer, 2000]. Piqueux *et al.* [2003] were the first to define and map the distribution of spider features in the ‘Cryptic’ region, which stretches across 73° - 81°S and is covered by seasonal CO₂ slab ice each winter [Kieffer *et al.*, 2000]. Spiders, often called araneiforms, are formed when solar irradiation is incident on a thick, low albedo CO₂ ice slab, which propagates deep into the ice, supplying energy to the underlying regolith. This process begins soon after the polar night has ended and continues throughout ice cap retreat. As the regolith warms, it reradiates energy causing basal sublimation of the CO₂ ice slab. Due to the very low porosity of the ice, CO₂ gas accumulates

beneath the ice, until the cryostatic pressure is exceeded and the ice slab ruptures to form a vent. If occurring under high enough pressure, venting can mobilise regolith material, which is redeposited on top of the ice slab in a fan formation. In the southern polar region, CO₂ venting has carved radial channels into the underlying bedrock, creating a weak point in the next seasonal ice cover, causing araneiforms to occur in the same places year on year [Kieffer, 2007; Kieffer et al., 2006; Kieffer et al., 2000; Martínez et al., 2012; Pilorget et al., 2013; Pilorget et al., 2011].

Seasonal furrows are similar features which have been observed in the northern polar erg. However, these are ephemeral due to sediment infill of the channels each year, blown by the summer winds which sculpt the extensive dune fields of this region [Bourke and Cranford, 2011; Bourke, 2013; Hansen et al., 2011; Hansen et al., 2013; Portyankina et al., 2017]. Furrows have been observed across 95% of the northern polar dunes as well as a band across the southern hemisphere stretching from 40° to 70° S [Nash and Bourke, 2015]. Furrows and araneiforms typically have a similar morphology, occurring as radially branching erosional features with a central pit, but vary with scale and longevity. Individual araneiforms can range from a few tens of metres to 1 km in diameter, with multiple interconnected branching tributaries up to 2 m deep and 5 m wide [Hansen et al., 2010; Portyankina et al., 2013], and are estimated to be in the region of 1,300 – 10,000 years old [Piqueux and Christensen, 2008; Portyankina et al., 2017]. Seasonal furrows, on the other hand, can also occur as ‘curvilinear’ features, and are both shallow and narrow at ~0.25 m and ~1.5 m respectively [Bourke and Cranford, 2011; Bourke, 2013]. All features, however, are thought to occur via the CO₂ jetting process, and involve the transportation of material from under the ice sheet and the break up of the seasonal ice cap, requiring a solid-state greenhouse to be induced.

Other features linked to the presence of surface CO₂ ice include gullies and ‘Swiss Cheese terrain’. Gullies are geologically young features consisting of tapered channels which transport material from an upslope alcove to a basal depositional apron, often reaching several kilometres in length [Balme et al., 2006; Dickson et al., 2007; Heldmann, 2005; Heldmann et al., 2007; Heldmann and Mellon, 2004]. Gullies are typically found on poleward facing slopes across the 30° – 50° latitude range in both hemispheres. The current formation mechanism for these features was proposed by Pilorget and Forget [2016], who suggest that the CO₂ jetting model (as per the Kieffer model of araneiform formation [Kieffer, 2000; Kieffer et al., 2006; Kieffer, 2007]) is capable of triggering mass movements when jetting is initiated on a slope.

Unusual landforms observed in the SPRC have been described as lobate features, which form a combination of troughs, mesas, and quasi-circular flat bottomed pits. These are collectively referred to as ‘Swiss Cheese terrain’ [Thomas et al., 2013; Thomas et al., 2009; Thomas et al., 2005]. Swiss Cheese terrain is associated with a layer of CO₂ ice 2 – 10 m in thickness, which overlies the permanent polar cap at the south pole, and its landforms are thought to be sublimation features. The ‘citizen science’ powered study by Schwamb et al. [2018] mapped the distribution of different high latitude surface features on Mars, and found that there was no location where araneiforms and Swiss Cheese coexisted, and Swiss Cheese only occurred within the SPRC. As the SPRC is the only place CO₂ ice is exposed all year round, which is highly eroded, higher albedo ice [Byrne and Ingersoll, 2003; Thomas et al., 2000; Thomas et al., 2013], understanding the penetration depth of smaller grained, inherently higher albedo CO₂ ice could aid in understanding the evolution of Swiss Cheese Terrain.

1.3 Granular Ices on Mars

Surface ice deposits of varying granularity are likely to be present due to more processes than just snowfall and frost formation. During spring, increased solar irradiation initiates the process of CO₂ jetting and the subsequent formation of araneiforms and furrows. It is also likely that increased daytime insolation could cause cracking due to thermal expansion/contraction cycles. Both of these processes result in localised break-up of the ice slab into smaller pieces.

Langevin et al [2006] reported on the observed near-infrared spectra of the ‘Cryptic’ region, obtained using the Thermal Emission Spectrometer (TES) on board the Mars Global Surveyor (MGS) and the OMEGA visible/near-infrared spectrometer on Mars Express. This region is located from 60°E to 210°E at around 80°S, and so lies within the southern seasonal polar cap and is where araneiforms are commonly observed [e.g. *Schwamb et al.*, 2018]. The strongest CO₂ ice signatures were observed in midwinter ($L_s=140^\circ$) at ~60°S. However, from soon after the spring equinox (which occurs at $L_s=180^\circ$), the seasonal cap was observed from cap edge to pole, but exhibited a very weak spectral signature for CO₂ ice which is not consistent with the prevailing theory of a thick, transparent CO₂ slab in this region. Instead, the best-fit modelled spectra suggest that, through $L_s=185^\circ$ - $L_s=197.3^\circ$, a surface layer of CO₂ granules ~5 mm thick, contaminated by 0.7 wt.% dust and 0.06 wt.% H₂O ice, overlies a slab of CO₂ ice approximately 150 mm thick. Following this, spectra from $L_s=223.2^\circ$ are best fitted by a thin granular upper layer 0.5 – 1.0 mm thick consisting of 7 wt.% dust particles ~10 μm in size, 0.4 wt.% H₂O ice particles of around 10 mm in diameter, and CO₂ ice granules which protrude above the surface at 5 mm in size, again overlying a >150 mm thick CO₂ ice slab. This level of dust contamination has the potential to inhibit araneiform formation. But by $L_s=241.9^\circ$, the CO₂ ice bands in the spectra are saturated, indicative of a clear CO₂ slab > 50 mm in thickness. *Kieffer et al.* [2006] argue that this sequence of events actually supports the CO₂ jetting model, as, at the time of the first observations venting and subsequent dark spot/fan deposition has already been underway for ~30 sols, with much of the araneiform terrain already having reached its final configuration. The layer of granular CO₂ ice, and the contamination by water ice and dust particles on the surface of a CO₂ slab is a direct result of CO₂ jetting activity and the transportation of basal regolith material to the surface.

Wind-blown dust can also be deposited on the surface of the ice, but the fact that, by $L_s=241.9^\circ$, the CO₂ slab is once again completely clean is evidence of a dust removal process. This ‘self-cleaning’ process occurs because solar radiation is absorbed more rapidly by dust grains than by ice due to the much lower albedo of dust. The dust re-radiates this energy, initiating sublimation of the surrounding ice, which causes the grain to burrow down through the ice pack until it is ejected from the bottom of the ice or can no longer receive sufficient insolation to trigger sublimation. The burrow left behind is likely to reseal rapidly due to the overlying gas and ice receiving little heat from the grain, and so freezes, thus maintaining low slab porosity [*Kieffer*, 2000; *Kieffer*, 2007; *Portyankina et al.*, 2010]. The depth of ice to which this process occurs is dependent upon how well radiation can penetrate into the ice column, which could be modelled if the penetration depth is known.

1.4 Physical Properties of Ices

Under laboratory-controlled Martian conditions, CO₂ ice is isotropic with a cubic crystal structure, but density is temperature dependent [*Mangan et al.*, 2017]. This strong temperature dependence of density causes thermal cracking of CO₂ ice. *Mangan et al.* [2017]

showed that the thermal expansion of CO₂ ice is much larger than for hexagonal H₂O ice over the same temperature range (80 – 195 K), as can be seen in Figure 1.

Over any given temperature range, CO₂ ice expands (or contracts) significantly more than water ice. Therefore, there is potential for extensive thermal cracking to occur in the seasonal CO₂ ice cap once the polar night has ended and solar radiation illuminates the ice sheet, increasing the amplitude of the diurnal temperature cycle. The strength of solid CO₂ ice is only 10% - 33% the strength of water ice under equivalent conditions [Clark and Mullen, 1976]. Consequently, it is possible that slabs of CO₂ ice constrained by topography undergo internal cracking due to thermal expansion, forming granular deposits in the zones of weaknesses.

Whilst accumulations of granular ice may not be particularly long-lived if the particles are small - microphysical models suggest surface sintering could occur rapidly, removing particles less than 1 mm in a matter of days [Clark *et al.*, 1983; Eluszkiewicz, 1993; Eluszkiewicz *et al.*, 2005] – larger particles or those below the immediate surface could remain stable for much longer. Sintering is the process of grain growth and densification in order to achieve the preferred thermodynamic state of minimum surface energy, and effectively changing the size of the grains, so increasing the penetration depth in those grains [Eluszkiewicz, 1993]. Some fine-grained deposits have indeed been observed over longer timescales, although these are thought to be locations of frequent snowfall [Hayne *et al.*, 2012].

In a recent experimental study by Portyankina *et al.* [2018], CO₂ was frozen under different pressure and temperature conditions to explore the effect on texture and ice transparency. A wide range of CO₂ ice textures formed depending on the exact P-T formation conditions, including (but not limited to) CO₂ crystals resembling snowflakes (generated at 24 mbar pressure, temperature of 160 K), a continuous translucent layer akin to slab ice (at 55 mbar pressure, temperature of 140 K), and multicrystal CO₂ ice of small hollow triangular prisms (at 7 mbar pressure, temperature of 125 K). Of particular interest was the formation of slab ice under Martian conditions for the first time, which occurred most often at pressures and temperatures close to the thermodynamic equilibrium between solid and gas phases. Under typical P-T conditions for the polar regions of Mars, CO₂ ice deposits in slab form, via a range of mechanisms and forming slab ice of varying translucency. The quality of the slab ice depends on the extent of cracking, water ice contamination, and general variations in opacity, or ‘cloudiness’ of the ice. This indicates that whilst it is expected to find slab ice during both growth of the ice sheet and break up during spring from higher insolation levels, discontinuous or granular ice could be present in varying grain sizes, or with a range of effective grain sizes between cracks in the slab.

1.5 Optical Properties of Ices

Electromagnetic waves propagating in a medium are attenuated by scattering and absorption. When a homogenous, isotropic material is subjected to incident irradiation, the intensity (I) of that radiation is attenuated exponentially with depth (z) through that medium:

$$I = I_0 e^{-z/\zeta} \quad (1)$$

Where the penetration depth ζ , or e-folding scale, is the thickness of material required to reduce the downward directed energy to $1/e$, of its initial intensity. Theoretically, $\zeta = \frac{1}{\alpha}$, where α is the absorption coefficient.

A number of assumptions are made when applying equations of geometrical optics to actual light intensity measurements of real-world materials, especially if those are particulate materials such as granular ices. Particle size should be larger than wavelength, else a different method is required to describe the scattering behaviour, e.g. Mie Theory or Rayleigh scattering [Bohren and Barkstrom, 1974]. Light travels through granular material differently than when passing through solid material. At small grain sizes scattering dominates; light travels via multiple reflections rather than passing through the ice, which is why snow appears white. On the other hand, solid sheets of non-porous ice are highly translucent to visible light, and so take on the appearance of the underlying material, such as in "black ice". This slab ice is observed extensively in the polar seasonal ice deposits, and notably in the 'Cryptic' region, where surface temperatures show CO₂ ice to be present, but the albedo matches that of bare regolith. Radiation intensity is only exponentially decayed by a purely absorbing material, with no internal scattering [Brandt and Warren, 1993]. However, a uniform medium which both absorbs and scatters exhibits attenuation which can be approximated to an exponential decay, if the optical depth is sufficient. Kaufmann and Hagermann [2015] showed that snow reached this exponential regime after only a few millimetres, and so the use of these equations are a sufficient approximation for our experiments. A rapid decrease in light intensity through the material, whether due to scattering or absorption, will result in a small e-folding scale.

Generally, in materials which are highly transparent at visible wavelengths, extinction is dominated by scattering. Due to this, attenuation by particles of said material is quite different from that of the bulk solid. As long as particle size is $>\lambda$, extinction dominated by scattering is virtually independent of photon energy [Bohren and Huffman, 1983]. The absorption coefficient is proportional to the scattering coefficient, which is inversely proportional to grain size d . This is because smaller grains in a fixed volume result in a greater number of scattering interfaces. However, this does not mean that the absorption coefficient or the refractive index of the bulk material should be disregarded, as absorption is fundamentally proportional to the mass of the material, whilst scattering is related to morphology [Schwerdtfeger and Weller, 1977]. Therefore, a comprehensive model describing the penetration depth in translucent granular material would require both absorption and scattering to be accounted for.

2. Methodology

CO₂ ice samples were prepared by condensing CO₂ directly from the gas phase within a pressure vessel cooled by liquid nitrogen, following the methodology detailed in *Chinnery et al.* [2018] and based on that used by *Kaufmann and Hagermann* [2017]. This formed large cylinders of CO₂ ice, which were then broken up and sieved. Water ice was made from deionised water, first boiled and then slowly frozen to minimise air bubbles in the ice. The difference between ‘snow’ (as measured previously in *Chinnery et al.*, 2019) and small granular ice is an important distinction, even though the grain size ranges overlap. Snow samples were made by spraying deionised water droplets into liquid nitrogen, and CO₂ snow was made using an Air Liquide Snowpack maker, connected directly to a liquid CO₂ cylinder, both of which made very fine, near-spherical droplets which tend to clump together, making grain size determination difficult (other than being sieved to <1.18 mm). Conversely, granular ice was made by processing blocks of preformed solid ice. This formation method created more angular, individual grains, analogous to what would be formed by breaking up naturally occurring ice deposits. Examples of the granular ice samples prior to sieving, therefore exhibiting a range of grain sizes and shapes, can be seen in Figure 2, where they can be compared to the alternative ‘snow’ morphology.

Each grain size range was acquired by the use of an upper and lower mesh size sieve: for use with water ice these were simply cooled in the freezer to approximately -40°C, and the whole process took place inside a chest freezer to keep temperatures low and frost to a minimum; for processing CO₂ ice the sieves were pre-cooled in a dewar vessel, with liquid nitrogen poured through them, the lid placed on, and left to cool to the temperature of the liquid nitrogen. The grains of CO₂ ice were sieved inside the dewar, therefore maintaining near- liquid nitrogen temperatures. In between samples, the sieves were removed from the dewar to warm up to room temperature and left to dry completely before repeating the process. This was to remove any small amounts of frost which accumulated on the cold metal surfaces of the sieve (mostly focussed on the outside walls of the sieves) due to ambient levels of moisture in the air. By repeating the chilling, sieving, warming and drying process, instead of sieving all samples back to back, contamination by water frost was minimised. Samples were temporarily stored in a sealed insulated container in the freezer at -86°C. This material was then treated similarly to snow for the light intensity measurements by *Chinnery et al.* [2019]. The sieve sizes used for both the H₂O and CO₂ granular ice experiments were: 0.355 mm, 0.50 mm, 0.60 mm, 0.71 mm, 0.85 mm, 1.00 mm, 1.18 mm, 2.00 mm, 3.35 mm, 4.00 mm, 5.60 mm, and 8.00 mm.

Once sieved, the ice granules within each grain size range were quite similar in shape to each other, although we acknowledge there was variation in general shape between grain size ranges. *Libois et al.* [2013 and 2014] conducted thorough investigations into the influence of grain shape on the absorption of solar radiation in terrestrial snowpacks. A wide range of naturally occurring grain shapes were identified in these studies, which were assigned values for the absorption enhancement parameter B ranging 0.7 – 2.4, whereas $B = 1.25$ for spherical grains. The absorption enhancement parameter quantifies the lengthening of the photon path inside grains due to multiple internal reflections, meaning that the e-folding scale can be over-estimated by ~30% in computational models when compared to real-world measurements [*Libois et al.*, 2014]. This highlights the need for laboratory measurements of the penetration depth of broad-spectrum light into snow and ice samples, rather than solely relying on theoretical models. Whilst there is no specific control for grain shape within this study, we believe the range of shapes present within the samples is more

analogous to naturally occurring samples, than using artificially spherical grains, and variations occurring to the range of grain shapes are covered within the error margins of the data.

Ice samples were held in stacked copper rings, forming a cylindrical sample container. The sample was then placed into the experimental chamber, which was accessed via a hole in the top beneath the mirror (see Figure 3). Inside, the chamber was black to prevent scattered stray light being recorded by the pyranometer and was insulated to maintain cold temperatures. Once in place, the samples were manipulated via gloves sealed into the side of the chamber. The height of the sample could be decreased in 5 mm increments by removing individual copper rings, and then scraping the sample surface flat using a silicone spatula across the top of the sample holder. By using this method, the volume of ice was kept consistent from sample to sample. Ice samples were irradiated using a solar simulator lamp (model LS1000R3, Solar Light Company), which utilises a Xenon arc lamp and specialised filters to closely match the full spectral radiance of the sun in space. Therefore, this is a good approximation for the radiation received on Mars, excluding any minor effects from Mars's atmospheric composition, clouds or suspended dust. Light from the lamp is directed via the mirror to be incident perpendicular on the surface of the sample (see experimental configuration shown in Figure 3). Light intensities were recorded using a multimeter connected to the pyranometer (CS300, Campbell Scientific Ltd.) which is sensitive across the wavelength range of 300 – 1100 nm placed directly beneath the sample, in the centre of the directed light beam. Measurements were made at four points for each sample thickness: once in the centre, then three radially around that central point. The mean of these measurements was determined and used to calculate the e-folding scale of each sample, in order to minimise the effect of any inhomogeneities (such as slight density variations, etc.). After the four measurements had been recorded at each given thickness, the top copper ring was removed, the sample scraped off again and light intensity measurements commenced. This process was repeated as necessary, in 5 mm thickness increments, and was all conducted inside the chamber flooded with cooled argon gas, which minimised both sintering and water frost contamination of the samples.

It was not deemed necessary for the measurements to be performed under Martian conditions for two reasons. Firstly, by calculating the e-folding scale from light intensity measurements at different thicknesses, the relative change in intensity is the defining variable, not the absolute light intensity. Because of this, terrestrial atmospheric pressure and composition would have made no measurable difference to the results, as long as conditions remained constant for the duration of the experiment. Secondly, throughout the course of the measurements, access was required to directly manipulate the samples, which would be very difficult if conducted within a vacuum chamber. As a consequence, efforts were taken to minimise the presence of water vapour, and maintain the cold temperatures required to keep the samples stable.

3. Results

The four results from the light intensity measurements at each sample thickness were averaged to give a mean light intensity per granular ice sample, per ice depth. Because reliable albedo measurements are difficult to obtain, only measurements taken at depths greater than that required to eliminate any possible albedo variations were used. In

accordance with the methodology used by *Kaufmann and Hagermann* [2015], for small ice grains the measurements taken at 5 mm depth were used as the zero point, and subsequent values normalised accordingly (so that calculations are made over the change in ice thickness, rather than absolute thickness). However, in our previous study [*Chinnery et al.*, 2018] it was found that a minimum ice depth of 8 mm was needed to remove the effects of albedo from slab ice measurements, and a greater range of ice thickness measurements was required due to the increased transparency of compact ice. The granular ice samples were measured in increments of 5 mm due to the copper ring sizes used to adjust sample height, and so at larger grain sizes the reference depth was increased to 10 mm, and depth range was also increased (see Table 1). The normalised values were then used to calculate the e-folding scale for those grain sizes, using Eq. 2, where the downward directed energy flux (F) is a function of ice thickness (x) and the penetration depth, or e-folding scale (ζ).

$$F(x) = e^{-x/\zeta}$$

(2)

The resulting e-folding scales for granular CO₂ and H₂O ice have been plotted in Figures 4 and 5 respectively. The horizontal error bars on both plots denote the range of grain sizes used in each experimental sample, and the vertical errors for the e-folding scale are an estimate based on experimental error, including device tolerance and human error. Generally, the penetration depth increases with increasing grain size, as would be expected, but not linearly.

In both types of ice, but most pronounced with CO₂ ice, there is greater data scatter at the smallest grain sizes. This is due to several factors: the smaller the grain size, the more rapid the sintering rate, and due to the volatility of CO₂ this was a greater effect. Whilst efforts were made to minimise this (e.g. using samples as quickly as possible after preparation, storing for the short periods required using liquid nitrogen to cool the samples, flooding the experimental chamber with cooled argon gas), it is likely that some sintering occurred when the grains were exposed to irradiation from the solar simulator. Similarly, with the smallest grains of water ice, a small amount of melting occurred when the solar simulator lamp was in operation. The chamber was cooled, but not to such cold temperatures as was used for CO₂ ice measurements. This is because, during testing, cooling the chamber too much caused the grains in contact with the glass base to stick, and made collecting multiple measurements difficult. All these issues were significantly less in the larger ice grain sizes. Due to this, we estimate the data errors on grain sizes <1.18 mm to be ± 3 mm, as used for the snow e-folding scale measurements by *Chinnery et al.* [2019], but for the larger grains >1.18 mm ± 2 mm.

4. Analysis

The penetration depth in ices is highly wavelength dependent, primarily because the absorption coefficient of bulk ice can vary by many orders of magnitude across the visible wavelength range. If grain size remains constant, then the penetration depth decreases with increasing wavelength. This is evidenced by the results of *Perovich* [1996] for the penetration depth of sea ice at different wavelengths, which ranged from 24 m at $\lambda = 470$ nm, 2 m at $\lambda = 700$ nm, to 0.05 m at $\lambda = 1000$ nm. It therefore follows that, as the penetration depth,

ζ , is proportional to grain size, d , if wavelength, λ , is held constant the penetration depth will increase with increasing grain size. *Li et al.* [2001] used this principle to model the penetration depths of different wavelengths in a 1 m thick snowpack as would be detected by the AVIRIS (Airborne Visible/Infrared Imaging Spectrometer) instrument. If we select the results from their model which are applicable to our wavelength range (300 nm – 1100 nm), the penetration depths are plotted in Figure 6, alongside a trendline for each wavelength specific relationship.

When plotted, the relationship between the data in Figure 6 follows the trend line:

$$y = a x^{0.5} \quad (3)$$

with a being wavelength dependent, y the penetration depth, and x grain size. Equation 3 forms the basis of the model derived here for H₂O and CO₂ ice granules. An iterative least-squares method was used to determine an empirical fit for the value of a , which was found to be constant for both ice compositions, based on the numbers retrieved by separate analysis for each ice composition being near equal, and the fact that the penetration depth of snow is the same for both compositions. This is logical given that the wavelength range used to irradiate the samples is constant for all measurements made (but it is this factor which varies with wavelength for the *Li et al.* [2001] data). However, if a is constant then grain size, x , must be scaled by a factor which is dependent on ice composition. This is because x should equal the effective diameter of non-spherical snow grains, which would be significantly smaller than the actual ice grain radius due to scattering from small internal features [*Domine et al.*, 2008]. Therefore, theoretically x should be scaled by a factor related to the scattering and absorption coefficients, and so would be compositionally specific. However, as the measurements presented here are made over a broad spectral range of 300 – 1100 nm, and the absorption coefficient for water and carbon dioxide ice increases by several orders of magnitude over these wavelengths, it would require integrating these values across these wavelengths and much more detailed measurements to derive this scaling factor theoretically from first principles. The iterative least squared process was repeated to determine the scaling factor, and x is substituted in the equation by grain diameter d and the scaling factor b .

The retrieved value of the scaling factor for water ice, rounded to the same number of significant figures $b \approx 0.031$. *Schwerdtfeger and Weller* [1977] made measurements of downwards-directed flux in naturally occurring snows at Plateau Station in Antarctica, and they determined from their data that the asymptotic flux extinction coefficient μ equals 0.030 scaled by grain diameter, d . *Schwerdtfeger and Weller* [1977] gave Eq. 4 as the relationship for calculating the light intensity I at a given depth of material z :

$$I = I_0 e^{-\mu z} \quad (4)$$

Comparing Eq. 1 with Eq. 4, it is clear that $\mu z = z/\zeta$, therefore $\mu = 1/\zeta$ [*Domine et al.*, 2008]. As $\mu z = 0.030/d$ [*Schwerdtfeger and Weller*, 1977], then $\zeta = d/0.030$. However, this simple relationship also does not explain our data on its own, but given the insignificant difference between this value, and that retrieved by *Schwerdtfeger and Weller* [1977], for the purposes of this study and the ability to predict the penetration depth of broad-spectrum solar irradiation in either water ice, this relationship can be substituted into our equation and 0.03

used as the scaling factor for water ice. There is no previous work to guide the scaling factor of CO₂ ice, and so we simply use the value retrieved by the least-squares method.

The dependence of the e-folding scale on grain size can be approximated by using the following equation, which can be seen plotted alongside the measurements in Figure 7:

$$\zeta = a + \left(\frac{d}{b}\right)^{0.5} \quad (5)$$

where $a = 5.370$, $b_{H_2O} = 0.030$, $b_{CO_2} = 0.0144$, and d = diameter of ice grain.

This formula (Eq. 5) provides an improved representation of the data for the broad spectrum measurements presented in this study.

This model is applicable for use across the visible spectrum, including the near-IR and near UV, for wavelengths 300 nm – 1100 nm, and up to a limited grain size, above which could be deemed to be slab ice (although at which point this occurs is still a matter for debate). Of itself, it does not take wavelength into account. As both the refractive index n and the absorption coefficient α are wavelength dependent, the ideal would be for these to be substituted into this equation. However, with our limited data we are unable to do this. The measured e-folding scales for granular ice, as presented in this study, are plotted in Figure 7. Additionally the e-folding scale of CO₂ slab ice, from *Chinnery et al.* [2018], and for both CO₂ and H₂O snow [*Chinnery et al.*, 2019] are also plotted in this graph.

So that direct comparisons can be made between ice compositions, light intensity measurements using slabs of water ice have also been undertaken, following the same methodology used for the CO₂ ice measurements (as detailed in *Chinnery et al.*, 2018). The model gives a good prediction of the e-folding scale up to the point at which slab ice is plotted. The ‘effective grain size’ was chosen for slab ice via digital analysis of photographs of the sample using the software ImageJ [*Schneider et al.*, 2012], with the smallest distance between cracks measured to be approximately 10 mm, and the largest 40 mm, whilst the effective grain size in water ice samples were determined to be larger at 15 – 45 mm. The lower panel of Figure 7 gives two examples of CO₂ slab ice samples, and two examples of H₂O slab ice samples (of eight which were analysed). Many of the water ice samples exhibited bubbles in the middle, and so measurements made in the centre of these samples (method exactly followed that of CO₂ slab ice measurements) were excluded from analysis when calculating the e-folding scale.

This model is a first approximation for quantifying the relationship between the penetration depths of broad-spectrum solar radiation in granular ice of different compositions. More extensive measurements are required to refine it further, with the aim of allowing for the optical properties of the ices to be fully integrated into the equation. This could also aid in defining an upper grain-size boundary, where the e-folding scale would plateau and remain

constant as would be applicable for the seasonal slab ice deposit observed during early spring in the Cryptic region of the southern polar cap.

5. Discussion

Results for the e-folding scale for granular ice deposits fit well with the previously published snow and slab ice results of $\zeta_{\text{snow}} = 11.2 \pm 3 \text{ mm}$ [Chinnery *et al.*, 2019], and on average $\zeta_{\text{CO}_2 \text{ slab}} = 47.6 \pm 2 \text{ mm}$, ranging up to $65.1 \pm 6.3 \text{ mm}$ for the best quality ice samples [Chinnery *et al.*, 2018]. Further to this, Portyankina *et al.* [2018] made light intensity measurements over the wavelength range 450 nm – 900 nm in CO₂ ice formed under Martian pressure and temperature conditions, which we have used to calculate the penetration depth of $\zeta_{\text{CO}_2 \text{ slab}} = 66.7 \text{ mm}$. This is in good agreement with the upper range for the penetration depth of CO₂ slab ice as measured in our previous experiments, despite the slightly narrower wavelength range used. It is likely that the Portyankina *et al.* [2018] results are slightly higher than those from Chinnery *et al.* [2018] due to the improvements in temperature and atmospheric control (therefore reducing imperfections within the ice), but it is nonetheless consistent within the error margins of our work. For both water and carbon dioxide ice, there is a clear trend from a regime of light propagation in ice composed of grains of the smallest sizes (snow, grain size $\leq 1 \text{ mm}$) to slab ice (grain size $\rightarrow \infty$), although the point at which it would be appropriate to transition from the ‘grain size’ model to slab ice regime is difficult to define, depending on how unblemished the slab ice is. Further measurements utilising samples of larger grains ($>8 \text{ mm}$), and of narrower grain size ranges, of CO₂ and H₂O ices would help determine this. However, the measurements and model of the e-folding scale have applications for all instances of granular ices on planetary bodies, including Earth, comets, and icy moons, in addition to Mars.

Specifically, accurate knowledge of light transmission through ice is needed for heat transfer models which can reliably predict surface atmosphere interactions on Mars when involving surface ice, such as frosts, snow falls, sintered snow and sintering rates as snow is metamorphosed into solid ice. This last point is particularly interesting, as the more sintered a snowpack becomes, the larger the effective grain size, and so the penetration depth increases. The resulting effect is that more visible light can penetrate through to the underlying regolith, although, if bulk porosity is decreased, more infrared wavelengths are absorbed by the ice itself due to the absorption bands exhibited by solid CO₂ [Warren, 1986; Quirico and Schmitt, 1997; Schmitt *et al.*, 1998; Hansen, 2005]. Thermal models, such as the study by Pilorget, *et al.* [2011] of CO₂ jetting in the seasonal ice sheet use theoretical values of penetration depths based on the optical properties of CO₂ ice and Mie scattering theory. These models are valuable tools but make a number of assumptions, including constant ice grain size and shape, with no density fluctuations and perfect uniformity to slab ice deposits, and are therefore likely to significantly overestimate the penetration depth in naturally occurring ices. Whilst the samples used in this study did not have a strict control on many of these factors, variations in grain shape and the presence of a small number of gas bubbles in the ice are much more likely to be analogous to naturally occurring, in situ ice deposits rather than idealised models.

Table 2 details the predicted e-folding scale values for a range of different CO₂ ice grain sizes which have been observed and/or inferred on the surface of Mars (detailed in Section 1.3). The amount of incident sunlight which could penetrate through to the base of the ice has been calculated as a percentage of the insolation received at the surface of the ice.

The actual extent of subsurface warming and whether this would lead to basal sublimation depends on many factors, not least the intensity of received insolation, thermal and mechanical properties of the underlying regolith, local temperature and pressure conditions, etc., which is beyond the scope of this study. However, it can be seen from these calculations that even a very fine covering of frost, e.g. a 0.5 mm thick deposit of grains 1 μm in diameter reduces insolation by 8.5% which could have significant implications for quenching CO_2 jetting if frost forms on top of a CO_2 slab. Fine grained CO_2 ice could be deposited on top of the ice by the jetting process itself via adiabatic cooling of the gas jets, which then settles out on the slab surface.

At the largest “effective grain size” of 0.5 m for a 1.5 m thick CO_2 slab, these estimates suggest only 0.04% of surface radiation reaches the bottom of the ice (not taking into account the potential error range of these data), which may not be sufficient to initiate basal sublimation and araneiform formation. These measurements could be used to put an upper constraint on ice thickness in regions where CO_2 jetting is active, or perhaps invoke a requirement for a certain proportion of absorbing impurities within the ice to induce sublimation within the ice itself.

Further work to refine this model would be beneficial, conducted by measuring the penetration depth in a range of different ices which occur on other planetary bodies in the solar system, such as methane, or icy mixtures. Furthermore, this would be improved by a greater range of more narrowly constrained grain size measurements and having improved thermal control over the ice samples, which would enable light intensity measurements in more pristine ice slabs, allowing for the maximum e-folding scale to be determined and placing an upper boundary on the model. Other aspects which could be integrated into the model would be the effect of contaminants, such as the measurements performed by *Kaufmann and Hagermann* [2015], who used Mars simulant JSC-1A to contaminate water snow samples and determine the effect on the penetration depth of broad-spectrum solar irradiation. If this were to be conducted using CO_2 snow then this would greatly improve our understanding of how the Martian polar regions behave, and further improve the modelling of araneiform and gully formation, for example.

6. Conclusions

The penetration depth of broad-spectrum (300 nm – 1100 nm) solar irradiation in granular ice has been calculated from light intensity measurements through water and carbon dioxide ices of different grain sizes. This was brought together with previous results giving the e-folding scale of H_2O and CO_2 snow, CO_2 slab ice and new measurements of H_2O slab ice. It has been found that the penetration depth varies with both grain size and composition in a manner which has been modelled within this study. It was found that whilst the penetration depth at small grain sizes (approximately ≤ 1 mm in diameter) is the same within the margins of experimental error; as grain size increases the impact of ice composition becomes more important. This is due to a greater proportion of light propagation occurring as transmission through the grains as opposed to scattering at the grain surfaces. As a consequence, the material properties of the ice, such as the refractive index and absorption coefficient, influence the penetration depth, alongside an inverse correlation with grain size. At larger grain sizes, increasing up to slab ice, the data clearly shows larger e-folding scales for CO_2 ice than H_2O ice. These results can be used to refine parameterisation of radiative transfer models for surface-atmosphere interactions for any planetary surface which hosts

either water or carbon dioxide ice. This is particularly relevant to the polar regions of Mars, where both water and carbon dioxide ices are present on the surface, but unique surface processes, such as CO₂ jetting, which gives rise to araneiforms, are only observed in the presence of CO₂ ice. A consistently higher e-folding scale of large grained carbon dioxide ice instead of water ice is a good explanation of these observations, as there is more energy from solar irradiation able to reach the underlying regolith, causing an enhanced solid-state greenhouse effect when compared to water ice.

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References

- Aharonson, O. (2004), Depth, distribution, and density of CO₂ deposition on Mars, *Journal of Geophysical Research*, 109(E5), doi:10.1029/2003je002223.
- Balme, M., N. Mangold, D. Baratoux, F. Costard, M. Gosselin, P. Masson, P. Pinet, G. Neukum, (2006), Orientation and distribution of recent gullies in the southern hemisphere of Mars: Observations from High Resolution Stereo Camera/Mars Express (HRSC/MEX) and Mars Orbiter Camera/Mars Global Surveyor (MOC/MGS) data, *Journal of Geophysical Research* 111(E5).
- Beaglehole, D., B. Ramanathan, and J. Rumberg (1998), The UV to IR transmittance of Antarctic snow, *Journal of Geophysical Research: Atmospheres*, 103(D8), 8849-8857, doi:10.1029/97jd03604.
- Bohren, C. F. and B. R. Barkstrom (1974). Theory of the optical properties of snow.- *Journal of Geophysical Research* 79(30): 4527-4535.
- Bohren, C. F., and D. R. Huffman (1983), *Absorption and Scattering of Light by Small Particles*, Wiley-Interscience, New York.
- Bourke, M., and A. Cranford (2011), Seasonal formation of furrows on polar dunes, in *Fifth Mars Polar Science Conference*, edited.
- Bourke, M. C. (2013), The formation of sand furrows by cryo-venting on Martian dunes, in *44th Lunar and Planetary Science Conference*, edited.
- Brandt, R., E., and S. Warren, G. (1993), Solar-heating rates and temperature profiles in antarctic snow and ice, *Journal of Glaciology*, 39(131), 99-110.
- Brown, A. J., S. Piqueux, and T. N. Titus (2014), Interannual observations and quantification of summertime H₂O ice deposition on the Martian CO₂ ice south polar cap, *Earth and Planetary Science Letters*, 406, 102-109, doi:10.1016/j.epsl.2014.08.039.
- Byrne, S., and A. P. Ingersoll (2003), A Sublimation Model for Martian South Polar Ice Features, *Science*, 299(5609), 1051-1053.
- Calvin, W. M. and T. Z. Martin (1994), Spatial Variability in the Seasonal South Polar Cap of Mars, *Journal of Geophysical Research* 99(E10): 143-152.

- Chinnery, H. E., A. Hagermann, E. Kaufmann, and S. R. Lewis (2018), The Penetration of Solar Radiation Into Carbon Dioxide Ice, *Journal of Geophysical Research: Planets*, 123(4), 864-871, doi:10.1002/2018je005539.
- Chinnery, H. E., A. Hagermann, E. Kaufmann, and S. R. Lewis (2019), The Penetration of Solar Radiation Into Water and Carbon Dioxide Snow, With Reference to Mars, *Journal of Geophysical Research: Planets*, 124(2), 337-348, doi:10.1029/2018je005771.
- Clark, B. R., and R. P. Mullen (1976), Martian Glaciation and the Flow of Solid CO₂, *Icarus*, 27, 215-228.
- Clark, R. N., F. P. Fanale, and A. P. Zent (1983), Frost Grain Size Metamorphism: Implications for Remote Sensing of Planetary Surfaces, *Icarus*, 56, 233-245.
- Datt, P., H. S. Gusain, and R. K. Das (2015), Measurements of Net Subsurface Heat Flux in Snow and Ice Media in Dronning Maud Land, Antarctica, *Journal Geological Society of India*, 86, 613-619.
- Dickson, J. L., J. W. Head, M. Kreslavsky (2007), Martian gullies in the southern mid-latitudes of Mars: Evidence for climate-controlled formation of young fluvial features based upon local and global topography, *Icarus*, 188(2), 315-323.
- Domine, F., M. Albert, T. Huthwelker, H.-W. Jacobi, A. A. Kokhanovsky, M. Lehning, G. Picard, and W. R. Simpson (2008), Snow Physics as relevant to Snow Photochemistry, *Atmospheric Chemistry and Physics*, European Geosciences Union, 8(2), 171-208.
- Egan, W., G., and F. A. Spagnolo (1969), Complex Index of Refraction of Bulk Solid Carbon Dioxide, *Applied Optics*, 8(11), 2359-2360.
- Eluszkiewicz, J. (1993), On the Microphysical State of the Martian Seasonal Caps, *Icarus*, 103, 13-48, doi:https://doi.org/10.1006/icar.1993.1056.
- Eluszkiewicz, J., J.-L. Moncet, T. N. Titus, and G. B. Hansen (2005), A microphysically-based approach to modeling emissivity and albedo of the martian seasonal caps, *Icarus*, 174(2), 524-534, doi:10.1016/j.icarus.2004.05.025.
- Forget, F. (1998), Mars CO₂ Ice Polar Caps, in *Solar System Ices*, edited by B. E. Schmidt, pp. 477-507, Springer Science & Business Media, B. V.
- Forget, F., G. B. Hansen, and J. B. Pollack (1995), Low brightness temperatures of Martian polar caps: CO₂ clouds or low surface emissivity? *Journal of Geophysical Research*, 100(E10), 21219-21234.
- Forget, F., and J. B. Pollack (1996), Thermal infrared observations of the condensing Martian polar caps: CO₂ ice temperatures and radiative budget, *Journal of Geophysical Research: Planets*, 101(E7), 16865-16879, doi:10.1029/96je01077.
- France, J. L., M. D. King, and A. MacArthur (2010), A photohabitable zone in the martian snowpack? A laboratory and radiative-transfer study of dusty water-ice snow, *Icarus*, 207(1), 133-139, doi:10.1016/j.icarus.2009.11.026.
- Genova, A., S. Goossens, F. G. Lemoine, E. Mazarico, G. A. Neumann, D. E. Smith, and M. T. Zuber (2016), Seasonal and static gravity field of Mars from MGS, Mars Odyssey and MRO radio science, *Icarus*, 272, 228-245, doi:10.1016/j.icarus.2016.02.050.
- Gillmann, C., P. Lognonné, E. Chassefière, and M. Moreira (2009), The present-day atmosphere of Mars: Where does it come from?, *Earth and Planetary Science Letters*, 277(3-4), 384-393, doi:10.1016/j.epsl.2008.10.033.
- Hansen, C. J., et al. (2011), Seasonal erosion and restoration of Mars' northern polar dunes, *Science*, 331(6017), 575-578, doi:10.1126/science.1197636.
- Hansen, C. J., S. Byrne, G. Portyankina, M. Bourke, C. Dundas, A. McEwen, M. Mellon, A. Pommerol, and N. Thomas (2013), Observations of the northern seasonal polar cap on Mars: I. Spring sublimation activity and processes, *Icarus*, 225(2), 881-897, doi:10.1016/j.icarus.2012.09.024.

Hansen, C. J., N. Thomas, G. Portyankina, A. McEwen, T. Becker, S. Byrne, K. Herkenhoff, H. Kieffer, and M. Mellon (2010), HiRISE observations of gas sublimation-driven activity in Mars' southern polar regions: I. Erosion of the surface, *Icarus*, 205(1), 283-295, doi:10.1016/j.icarus.2009.07.021.

Hansen, G. B. (2005), Ultraviolet to near-infrared absorption spectrum of carbon dioxide ice from 0.174 to 1.8 μm . *Journal of Geophysical Research*, 110(E1103). doi:10.1029/2005JE002531.

Hayne, P. O., D. A. Paige, and N. G. Heavens (2014), The role of snowfall in forming the seasonal ice caps of Mars: Models and constraints from the Mars Climate Sounder, *Icarus*, 231, 122-130, doi:10.1016/j.icarus.2013.10.020.

Hayne, P. O., D. A. Paige, J. T. Schofield, D. M. Kass, A. Kleinböhl, N. G. Heavens, and D. J. McCleese (2012), Carbon dioxide snow clouds on Mars: South polar winter observations by the Mars Climate Sounder, *Journal of Geophysical Research: Planets*, 117(E8), 1-23, doi:10.1029/2011je004040.

Heldmann, J. L. (2005). Formation of Martian gullies by the action of liquid water flowing under current Martian environmental conditions, *Journal of Geophysical Research*, 110(E5).

Heldmann, J. L., E. Carlsson, H. Johansson, M. T. Mellon, O. B. Toon, (2007), Observations of martian gullies and constraints on potential formation mechanisms. II. The Northern Hemisphere, *Icarus* 188(2): 324-344.

Heldmann, J. L. and M. T. Mellon (2004), Observations of martian gullies and constraints on potential formation mechanism, *Icarus* 168(2): 285-304.

Hudgins, D. M., S. A. Sandford, L. J. Allamandola, and A. G. G. M. Tielens (1993), Mid- and far-infrared spectroscopy of ices - Optical constants and integrated absorbances, *Astrophysical Journal Supplement Series*, 86(2), 713-870, doi:10.1086/191796.

Kaufmann, E., and A. Hagermann (2015), Penetration of solar radiation into pure and Mars-dust contaminated snow, *Icarus*, 252, 144-149, doi:10.1016/j.icarus.2015.01.007.

Kaufmann, E., and A. Hagermann (2017), Experimental investigation of insolation-driven dust ejection from Mars' CO₂ ice caps, *Icarus*, 282, 118-126, doi:10.1016/j.icarus.2016.09.039.

Kieffer, H. H. (2000), Annual Punctuated CO₂ Slab-Ice and Jets on Mars, in *Mars Polar Science*, edited, p. 4095.

Kieffer, H. H. (2007), Cold jets in the Martian polar caps, *Journal of Geophysical Research*, 112(E8), doi:10.1029/2006je002816.

Kieffer, H. H., P. R. Christensen, and T. N. Titus (2006), CO₂ jets formed by sublimation beneath translucent slab ice in Mars' seasonal south polar ice cap, *Nature*, 442(7104), 793-796, doi:10.1038/nature04945.

Kieffer, H. H., T. N. Titus, K. F. Mullins, and P. R. Christensen (2000), Mars south polar spring and summer behavior observed by TES: Seasonal cap evolution controlled by frost grain size, *Journal of Geophysical Research*, 105(E4), 9653, doi:10.1029/1999je001136.

Kuroda, T., A. S. Medvedev, Y. Kasaba, and P. Hartogh (2013), Carbon dioxide ice clouds, snowfalls, and baroclinic waves in the northern winter polar atmosphere of Mars, *Geophysical Research Letters*, 40(8), 1484-1488, doi:10.1002/grl.50326.

Langevin, Y., Bibring, J.P., Montmessin, F., Forget, F., Vincendon, M., Douté, S., Poulet, F. and Gondet, B. (2007). Observations of the south seasonal cap of Mars during recession in 2004–2006 by the OMEGA visible/near-infrared imaging spectrometer on board Mars Express. *Journal of Geophysical Research*, 112(E8).

Langevin, Y., S. Doute, M. Vincendon, F. Poulet, J. P. Bibring, B. Gondet, B. Schmitt, F. Forget (2006), No signature of clear CO₂ ice from the 'cryptic' regions in Mars' south seasonal polar cap, *Nature* 442(7104): 790-792.

Langevin, Y., J. P. Bibring, F. Montmessin, F. Forget, M. Vincendon, S. Doute, F. Poulet, B. Gondet, (2007), Observations of the south seasonal cap of Mars during recession in 2004–2006 by the OMEGA visible/near-infrared imaging spectrometer on board Mars Express, *Journal of Geophysical Research*, 112(E8).

Langevin, Y., F. Poulet, J. P. Bibring, J. P., B. E. Schmidt, S. Douté, B. Gondet, (2005). Summer Evolution of the North Polar Cap of Mars as Observed by OMEGA/Mars Express. *Science* 307(5715): 1581-1584.

Li, W., K. Stamnes, B. Chen, and X. Xiong (2001), Snow grain size retrieved from near-infrared radiances at multiple wavelengths, *Geophysical Research Letters*, 28(9), 1699-1702, doi:10.1029/2000gl011641.

Libois, Q., G. Picard, J. L. France, L. Arnaud, M. Dumont, C. M. Carmagnola, and M. D. King. 2013. 'Influence of grain shape on light penetration in snow', *The Cryosphere*, 7: 1803-18.

Libois, Quentin, Ghislain Picard, Marie Dumont, Laurent Arnaud, Claude Sergent, Evelyne Pougatch, Marcel Sudul, and David Vial. 2014. 'Experimental determination of the absorption enhancement parameter of snow', *Journal of Glaciology*, 60: 714-24.

Maass, O., and W. H. Barnes (1926), Some Thermal Constants of Solid and Liquid Carbon Dioxide, *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, 111(757), 224-244.

Mangan, T. P., C. G. Salzmann, J. M. C. Plane, and B. J. Murray (2017), CO₂ ice structure and density under Martian atmospheric conditions, *Icarus*, doi:10.1016/j.icarus.2017.03.012.

Martínez, G. M., N. O. Renno, and H. M. Elliott (2012), The evolution of the albedo of dark spots observed on Mars polar region, *Icarus*, 221(2), 816-830, doi:10.1016/j.icarus.2012.09.008.

Matson, D. L., and B. H. Brown (1989), Solid-State Greenhouses and Their Implications for Icy Satalites, *Icarus*, 77, 67-81.

Matsuo, K., and K. Heki (2009), Seasonal and inter-annual changes of volume density of Martian CO₂ snow from time-variable elevation and gravity, *Icarus*, 202(1), 90-94.

Nash, C. and M. Bourke (2015). Southern hemisphere sand furrows: spatial patterning and implications for the cryo-venting process. EGU General Assembly. Vienna, Austria, Copernicus.

Möhlmann, D.T.F. (2010), Temporary liquid water in upper snow/ice sub-surfaces on Mars? *Icarus* 207, 140–148, doi.org/10.1016/j.icarus.2009.11.013.

Perovich, D. K. (1996), *The Optical Properties of Sea Ice*, in Monograph 96-1, edited, Office of Naval Research.

Pilorget, C., C. S. Edwards, B. L. Ehlmann, F. Forget, and E. Millour (2013), Material ejection by the cold jets and temperature evolution of the south seasonal polar cap of Mars from THEMIS/CRISM observations and implications for surface properties, *Journal of Geophysical Research: Planets*, 118(12), 2520-2536, doi:10.1002/2013je004513.

Pilorget, C., F. Forget, (2016), Formation of Gullies on Mars by Debris Flows Triggered by CO₂ Sublimation, *Nature Geoscience*, 9(1), 65-69.

Pilorget, C., F. Forget, E. Millour, M. Vincendon, and J. B. Madeleine (2011), Dark spots and cold jets in the polar regions of Mars: New clues from a thermal model of surface CO₂ ice, *Icarus*, 213(1), 131-149, doi:10.1016/j.icarus.2011.01.031.

Piqueux, S., S. Byrne, and M. I. Richardson (2003), Sublimation of Mars's southern seasonal CO₂ ice cap and the formation of spiders, *Journal of Geophysical Research*, 108(E8), doi:10.1029/2002je002007.

Piqueux, S., S., and P. R. Christensen (2008), North and south subice gas flow and venting of the seasonal caps of Mars: A major geomorphological agent, *Journal of Geophysical Research*, 113(E6), doi: 10.1029/2007je003009.

- Piqueux, S., A. Kleinböhl, P. O. Hayne, N. G. Heavens, D. M. Kass, D. M. McCleese, J. T. Scholfield, J. H. Shirley (2016), Discovery of a widespread low-latitude diurnal CO₂ frost cycle on Mars, *Journal of Geophysical Research: Planets* 121.
- Portyankina, G., C. J. Hansen, and K.-M. Aye (2017), Present-day erosion of Martian polar terrain by the seasonal CO₂ jets, *Icarus*, 282, 93-103, doi:10.1016/j.icarus.2016.09.007.
- Portyankina, G., W. J. Markiewicz, N. Thomas, C. J. Hansen, and M. Milazzo (2010), HiRISE observations of gas sublimation-driven activity in Mars' southern polar regions: III. Models of processes involving translucent ice, *Icarus*, 205(1), 311-320, doi:10.1016/j.icarus.2009.08.029.
- Portyankina, G., J. Merrison, J. J. Iversen, Z. Yoldi, C. J. Hansen, K. M. Aye, A. Pommerol, and N. Thomas (2018), Laboratory investigations of the physical state of CO₂ ice in a simulated Martian environment, *Icarus*, doi:10.1016/j.icarus.2018.04.021.
- Portyankina, G., A. Pommerol, K.-M. Aye, N. Thomas, S. Mattson, C.J. Hansen, 2013, Influence of small scale topography on early spring activity in Martian polar areas. An example study based on DEM of Inca City region. In: 2013 European Planetary Science Congress (Abstract 2013-410).
- Quirico, E., and B. Schmitt (1997), Near-Infrared Spectroscopy of Simple Hydrocarbons and Carbon Oxides in Solid N₂ and as Pure Ices: Implications for Triton and Pluto, *Icarus*, 127, 354-378.
- Röttger, K., A. Endriss, J. Ihringer, S. Doyle, and W. F. Kuhs (2012), Lattice constants and thermal expansion of H₂O and D₂O ice Ih between 10 and 265 K. Addendum, *Acta crystallographica. Section B, Structural science*, 68(Pt 1), 91, doi:10.1107/S0108768111046908.
- Schneider, C., A., W. S. Rasband, K. W. Eliceiri (2012), NIH Image to ImageJ:25 Years of Image Analysis, *Nature Methods*, 9(7).
- Schwamb, M. E., K.-M. Aye, G. Portyankina, C. J. Hansen, C. Allen, S. Allen, F. J. Calef, S. Duca, A. McMaster, and G. R. M. Miller (2018), Planet Four: Terrains – Discovery of araneiforms outside of the South Polar layered deposits, *Icarus*, 308, 148-187, doi:10.1016/j.icarus.2017.06.017.
- Schwerdtfeger, P., and G. E. Weller (1977), Radiative Heat Transfer Processes in Snow and Ice, *Antarctic Research Series*, 25, doi:10.1029/AR025p0035.
- Smith, D. E., M. T. Zuber, and G. A. Neumann (2001), Seasonal Variations of Snow Depth on Mars, *Science*, 294, 2141 - 2146.
- Smith, P. H., L. K. Tamppari, R. E. Arvidson, D. Bass, D. Blaney, W. V. Boynton, A. Carswell, D. C. Catling, B. C. Clark, T. Duck, E. DeJong, D. Fischer, W. Goetz, H. P. Gunnlaugsson, M. H. Hecht, V. Hipkin, J. Hoffman, S. F. Hviid, H. U. Keller, S. P. Kounaves, C. F. Lange, M. T. Lemmon, M. B. Madsen, W. J. Markiewicz, J. Marshall, C. P. McKay, M. Mellon, D. W. Ming, R. V. Morris, W. T. Pike, N. O. Renno, U. Staufer, C. Stoker, P. Taylor, J. A. Whiteway, and A. P. Zent (2009) H₂O at the Phoenix Landing Site, *Science*, 325: 58-61.
- Spiga, Aymeric, David P. Hinson, Jean-Baptiste Madeleine, Thomas Navarro, Ehouarn Millour, François Forget, and Franck Montmessin (2017), Snow precipitation on Mars driven by cloud-induced night-time convection, *Nature Geoscience*, 10: 652-57.
- Thomas, P. C., W. M. Calvin, P. Gierasch, R. Haberle, P. B. James, and S. Sholes (2013), Time scales of erosion and deposition recorded in the residual south polar cap of Mars, *Icarus*, 225(2), 923-932, doi:10.1016/j.icarus.2012.08.038.
- Thomas, P. C., P. B. James, W. M. Calvin, R. Haberle, and M. C. Malin (2009), Residual south polar cap of Mars: Stratigraphy, history, and implications of recent changes, *Icarus*, 203(2), 352-375, doi:10.1016/j.icarus.2009.05.014.
- Thomas, P. C., M. Malin, K. S. Edgett, M. H. Carr, W. K. Hartmann, A. P. Ingersoll, P. B. James, L. A. Soderblom, J. Veverka, and R. Sullivan (2000), North-South Geological Differences Between the Residual Polar Caps on Mars, *Nature*, 404.

Thomas, P. C., M. C. Malin, P. B. James, B. A. Cantor, R. M. E. Williams, and P. Gierasch (2005), South polar residual cap of Mars: Features, stratigraphy, and changes, *Icarus*, 174(2), 535-559, doi:10.1016/j.icarus.2004.07.028.

Vincendon, M., Forget, F. and Mustard, J. (2010). Water ice at low to midlatitudes on Mars. *Journal of Geophysical Research*, 115(E10).

Warren, S. G. (1986) Optical constants of carbon dioxide ice, *Applied Optics* 25(16): 2650-2674.

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Table 1. Granular ice depth ranges over which the e-folding scale was derived. The starting depth/‘zero point’ and the range of ice depth increased with larger grain sizes due to lower albedo and greater transparency of the sample.

Grain size range (mm)	Depth of measurements used to calculate e-folding scale (mm)	
	CO ₂	H ₂ O
0.355 – 0.50	5 – 10	5 – 10
0.50 – 0.60	5 – 10	5 – 10
0.60 – 0.71	5 – 10	5 – 10
0.71 – 0.85	5 – 10	5 – 10
0.85 – 1.00	5 – 10	5 – 10
1.00 – 1.18	5 – 10	5 – 10
1.18 – 2.00	5 – 15	5 – 15
2.00 – 3.35	5 – 20	5 – 20
3.35 – 4.00	10 – 25	10 – 25
4.00 – 5.60	10 – 30	10 – 30
5.60 – 8.00	10 – 30	10 – 30

Table 2. The e-folding scale of a CO₂ granular ice deposit, based on the e-folding scale grain size model, and the associated reduction in insolation intensity at the base of the ice deposit compared to the surface. * denotes where no ice depth estimate was available, so 10 mm has been used for comparison purposes.

Grain Size (mm)	E-folding Scale (mm)	Ice depth	Insolation reduction	References for grain size and ice thickness
0.001	5.63	0.1 mm	1.76 %	<i>Piqueux et al.</i> [2016]
		0.5 mm	8.50 %	
0.10	8.01	10 mm*	71.30 %	<i>Hayne et al.</i> [2014]
5.00	24.00	10 mm*	34.08 %	<i>Langevin et al.</i> , [2006]; <i>Langevin et al.</i> , [2007]
10.0	31.72	10 mm*	27.04 %	<i>Kieffer</i> [2000]; <i>Langevin et al.</i> , [2007]
100	88.70	10 mm	10.66 %	<i>Langevin et al.</i> , [2007]
200	123.22	0.2 m	80.27 %	<i>Langevin et al.</i> , [2007]; <i>Mitrofanov, et al.</i> [2003] <i>Langevin et al.</i> , [2007] <i>Kieffer</i> [2007]
		0.5 m	98.27 %	
		1.0 m	99.97 %	
500	191.71	0.5 m	92.63 %	<i>Langevin et al.</i> , [2007] <i>Kieffer</i> [2007]; <i>Mitrofanov, et al.</i> [2003] <i>Matsuo & Heki</i> [2009]; <i>Smith et al</i> [2001]
		1.0 m	99.46 %	
		1.5 m	99.96 %	

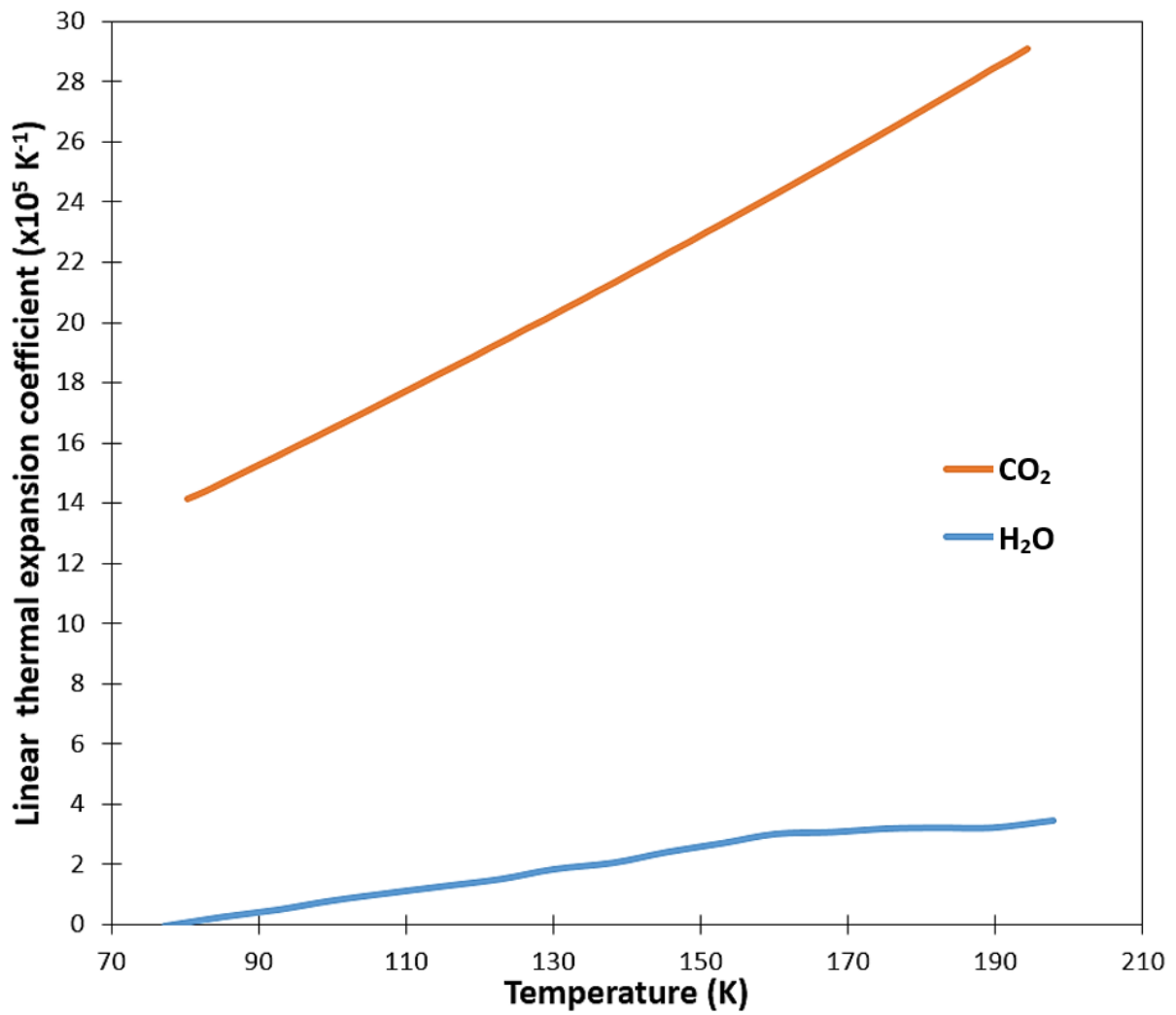


Figure 1. Linear thermal expansion coefficients ($\times 10^5$) for CO₂ ice (data from *Mangan et al.* [2017]) and H₂O ice (data taken from *Röttger et al.* [2012]).

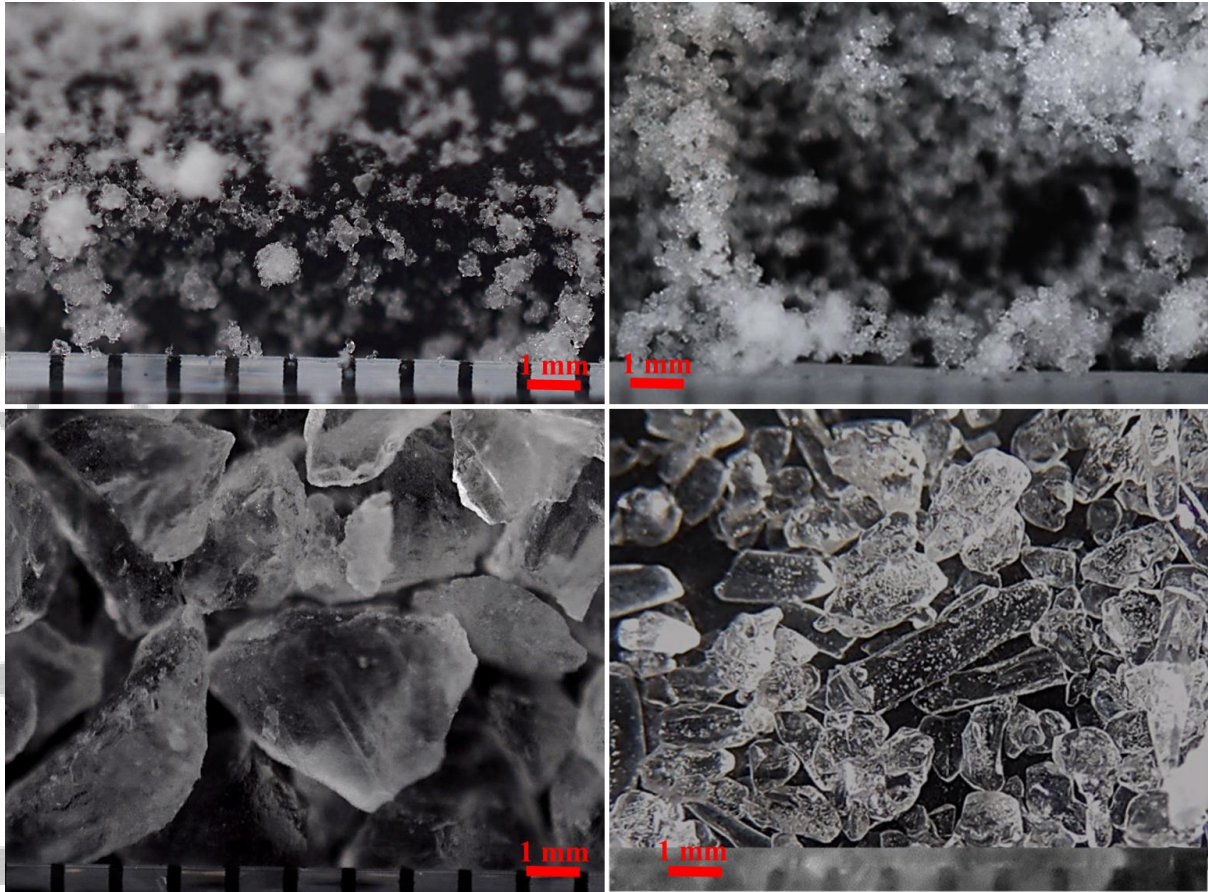


Figure 2. Top left: H₂O snow; top right: CO₂ snow; lower left, H₂O ice granules; lower right: CO₂ ice granules. All images are to the same scale. Granules are angular and irregularly shaped, but similar within each sample size range once sieved. Individual grains are of clear pure ice with little visible internal cracking or imperfections.

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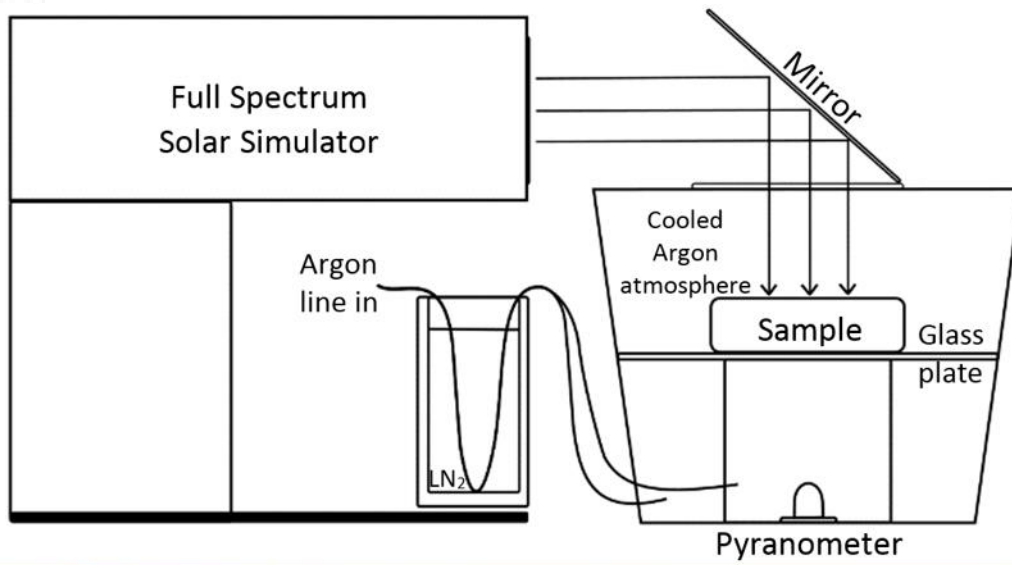


Figure 3. Equipment and experimental set-up used to conduct all light intensity measurements.

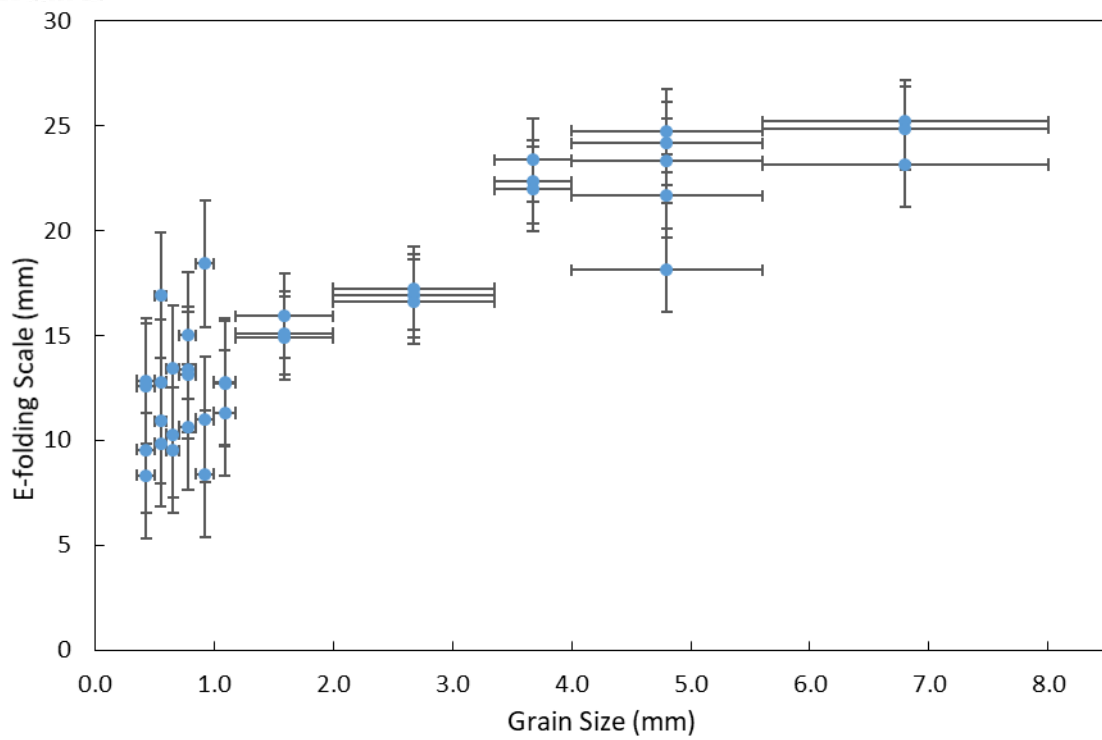


Figure 4. Results from light intensity measurements showing how the e-folding scale of granular CO₂ ice increases with increasing grain size.

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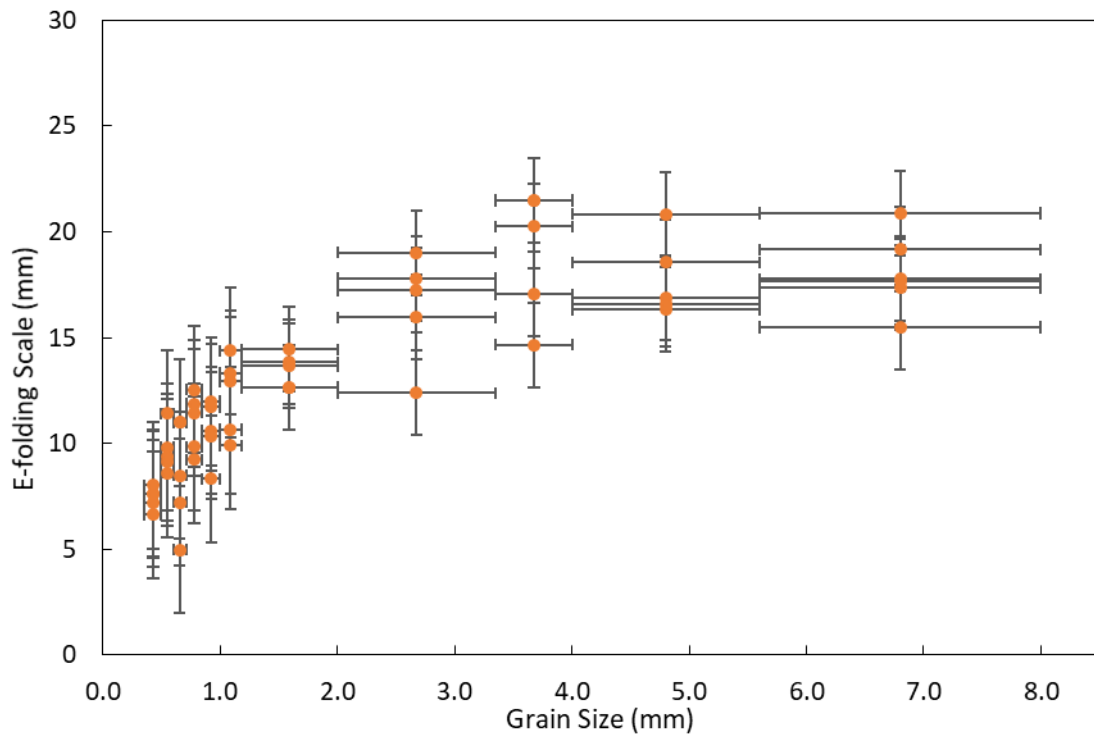


Figure 5. Results from light intensity measurements showing how the e-folding scale of granular H₂O ice increases with increasing grain size.

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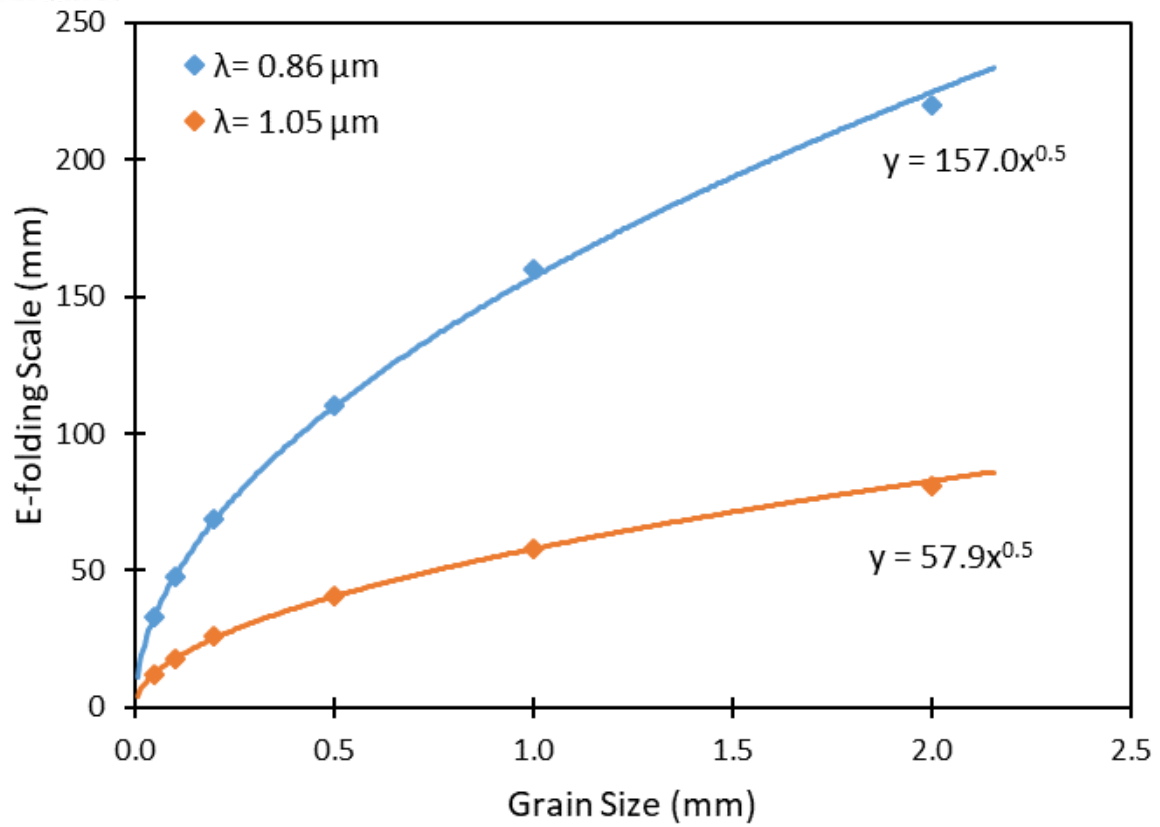


Figure 6. Selection of data based on applicable wavelength range from *Li et al.* [2001]: Penetration depths in snow of specified grain size at specific wavelengths. Trendlines fitted via least-squares method.

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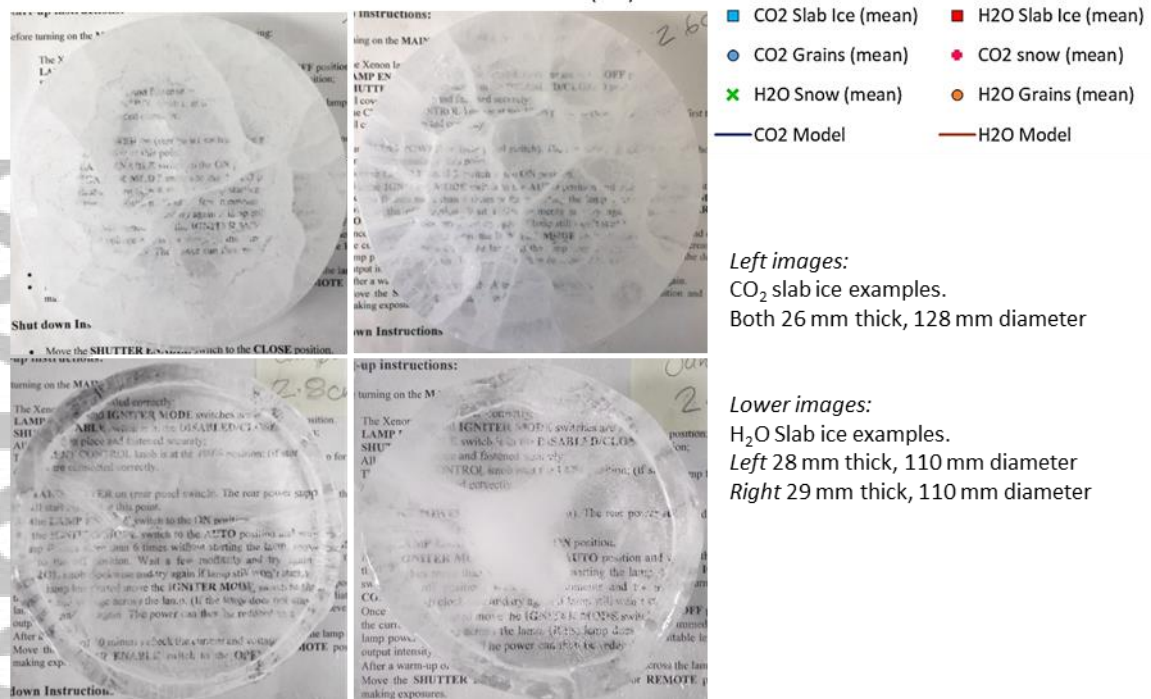
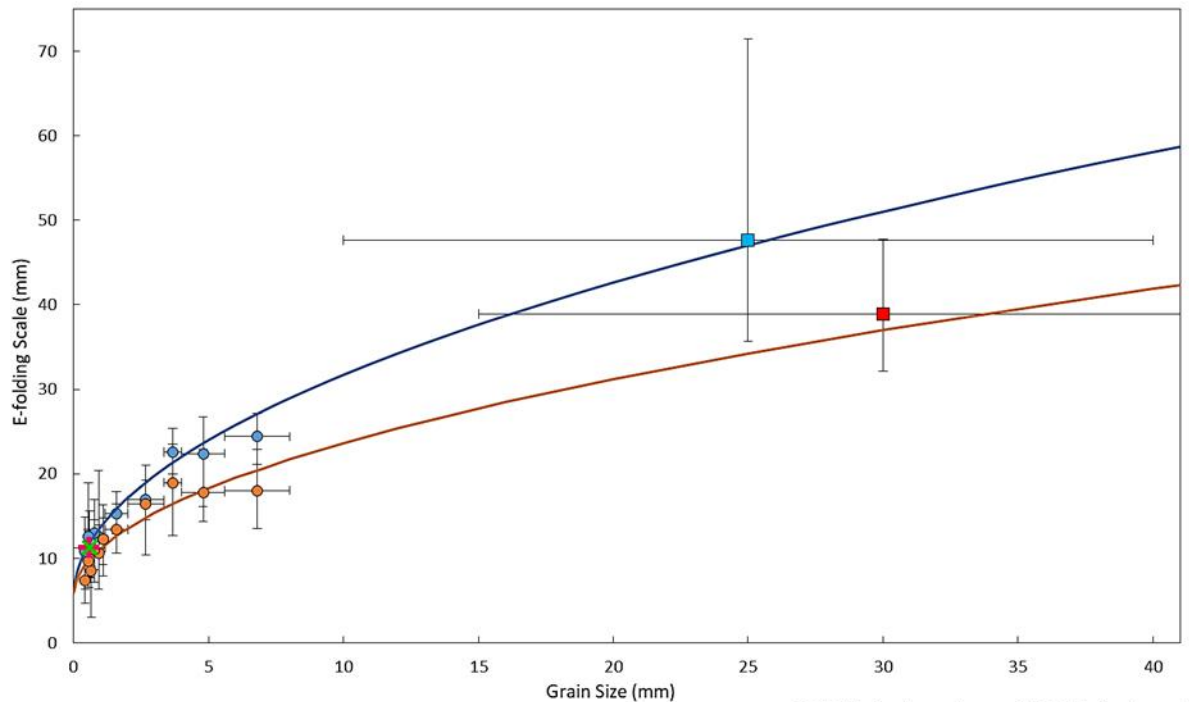


Figure 7. Top: the average (mean) e-folding scale is plotted for each grain size and ice composition. The e-folding scale of H₂O and CO₂ snow is plotted (data from Chinnery *et al.*, 2019), in addition to the results from slab ice experiments, of which the CO₂ slab ice e-folding scale was published in Chinnery *et al.* [2018]. Vertical error bars show the spread of data ± 2 mm for experimental errors, horizontal errors denote the grain size ranges. Note that both CO₂ and H₂O snow plot at the same location on the graph at $11.2 \text{ mm} \pm 3 \text{ mm}$ (see Chinnery *et al.*, 2019 for details).

Bottom images: examples of CO₂ (upper) and H₂O (lower) slab ice samples, which were digitally analysed to determine the “effective grain size range” of the samples in order to plot on the graph as horizontal error bars.