

Article

Microstructural Evolution of Antarctic Ice with the Rising Atmospheric CO₂: A Longitudinal Meta-Analysis

Vuk Uskoković ^{1,2,3} ¹ TardigradeNano, 7 Park Vista, Irvine, CA 92604, USA; vuk21@yahoo.com or

vuk.uskokovic@tardigradenano.com or vuskokovic@fullcoll.edu or uskokovi@chapman.edu

² Division of Natural Sciences, Fullerton College, 321 East Chapman Avenue, Fullerton, CA 92832, USA³ Schmid College of Science and Technology, Chapman University, 1 University Drive, Orange, CA 92866, USA

Abstract

Antarctica, largely free from geopolitical borders, serves as a critical site for scientific research, environmental monitoring and climate studies. The continent's ice cap holds over 60% of the Earth's freshwater and provides a stable climatological record spanning 800,000 years. In this study, the relationship between changes in atmospheric CO₂ levels over the past century and the microstructural characteristics of Antarctic ice was investigated. While it is well-documented that CO₂ fluctuations have driven the periodic expansion and retreat of ice sheets, no research to this day has explored how variations in CO₂ concentrations influence the physical integrity of ice at the microscopic scale. To address this, grain size, anisotropy, irregularity, and solidity of surface and near-surface ice samples collected over the past 70 years were analyzed. These microstructural features were compared against historical atmospheric greenhouse gas data from multiple Antarctic research stations, including records from the Scripps Institution of Oceanography, the Japanese Antarctic Research Expedition, and the NOAA Global Monitoring Laboratory. Results reveal a correlation between rising CO₂ levels and changes in ice microstructure, particularly an increase in the grain size as well as the reduction in the grain aspect ratio and in the morphological solidity. The study remains limited by significant sources of variability, including differences in sampling depths, geographical locations, seasonal effects, and inconsistencies in analytical tools and methodologies reported across the literature. Despite these limitations, this proof-of-concept study elicits the need for continued meta-analyses of existing climate datasets. Such efforts could provide deeper insights into the role of greenhouse gas concentrations in defining the microstructural stability of Antarctic ice, which is critical for predicting ice sheet integrity and its contribution to sea level rise.

Keywords: climate change; cryosphere dynamics; firn; global warming; greenhouse gases; materials chemistry; snow; water



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1. Introduction

Antarctica is the only continent on Earth that can be considered, with some degree of reservation [1,2], freed from classical geopolitical borders [3]. Albeit mainly uninhabited, hostile in terms of environmental conditions and nearly impossible to support self-sustained communities, Antarctica, like the planetary oceans and outer space, symbolizes a place belonging to every earthling equally. The 14-article Antarctic Treaty, signed on 1 December 1959 by a dozen countries [4], independently of the United Nations, ensures that this continent is used only for the promotion of peace, environmental protection and, perhaps

most importantly of all, scientific research. In fact, scientific research presents the main and oftentimes the only reason over 30 different countries cited as the one justifying their presence on this 14.2 million km² large continent [5]. Antarctica, in fact, houses hundreds of continuously active measurement stations, which produce data that are freely accessible, both historically and in real-time, through various online platforms and databases.

Most notably, the research conducted in Antarctica in the early 1980s led to the discovery of the ozone hole [6] and to the subsequent ban on the production and use of chlorofluorocarbons as refrigerants, which to this day represents the single greatest story on how environmental science can correct harmful industrial actions and restore damage made inadvertently to the planet by anthropogenic activities. Because Antarctica, despite being the largest desert on Earth, holds over 60% of the Earth's fresh water in the solid form and is also the fastest warming continent, it presents a site necessary to monitor for ice sheet disintegration to ensure that catastrophic scenarios entailing the melting of this polar cap are averted. It has been estimated that the complete melting of the ice in Antarctica, which, on average covers the 14.2 million km² continent with a 1.2 mile thick ice sheet, would raise the sea level by around 60 meters [7], which would necessitate the displacement of one quarter of the Earth's human population. Some of the global temperature increase induced by the melting of this ice and the consequent intensification of the greenhouse effect will be mitigated by the enhanced precipitation rate—predominantly around the coastal areas because their orographic obstruction would force the incoming winds to liberate the moisture concentrated around the most quickly warmed periphery of the continent—but this compensation effect is expected to be only partial [8].

On top of this, importantly, the Antarctic ice cap contains the most stable record of the Earth's climatological past. The ice sheet reaching thicknesses of nearly 3 miles in some areas of the continent traps gases present in the geological eras in which the ice was deposited, acting as the most reliable climate change record of all. This record extends 800,000 years into the past [9], roughly a thousand years for the first 100 meters into the depth, before beginning to gradually lessen the slope and partially plateau [10]. The European Project for Ice Coring in Antarctica (EPICA) has managed to deduce atmospheric CO₂ concentrations for the last 800,000 years based on the concentrations of this gas trapped at different depths of the ice cap and, importantly, show that atmospheric CO₂ levels of today are higher than they have ever been in the last 800,000 years [11].

It is widely known that variations in the concentration of CO₂ in the atmosphere have caused the periodic retreat and expansion of the Antarctic ice cap [12]. However, it has been seldom, if at all, inquired as to how changes in the environmental concentrations of CO₂ can affect the microstructural characteristics of ice. Critically, any weakening of ice caused by the disruption of its microstructural integrity can increase its propensity for melting and for the collapse of glaciers. As ice sheets fracture and split into multiple chunks, the greater degree of their volume becomes exposed to water, speeding up the retreat of the polar cap, raising the sea water level, reducing the reflectiveness of sunlight back into space and further contributing to global warming. The relationship between the alteration of the surface ice on Antarctica and the change in the CO₂ atmospheric levels in the last century, to this author's knowledge, has not been studied nor confirmed yet. This is where we arrive at the objective of this study, which is to assess and quantify ice crystal characteristics such as grain size, grain anisotropy, grain morphology irregularity and grain solidity as a function of the date when the samples were collected and compare them with the annual meteorological data on the atmospheric concentrations of CO₂ and other greenhouse gases over Antarctica in the past 70 years, as reported by the Scripps Institute of Oceanography, the Japanese Antarctic Research Expedition and the US National Oceanic

and Atmospheric Administration (NOAA) Global Monitoring Laboratory, searching for a possible correlation.

We, as the scientific community, have reached a stage where new data generation has far exceeded the ability to analyze and make sense of the given data, especially when it comes to infinitely numerous correlations that could be potentially established within such rapidly expanding datasets. This is why meta-studies, in which analyses of data collected by different research groups at different locations and different times are carried out, are now more important than ever [13–15]. In this study, one such meta approach was pursued, as data acquired by different research teams in the last 70 years were compared against data produced by three of the many continuously operating international measurement stations scattered across Antarctica. Eventually, it is shown that there is a direct correlation between the microstructural characteristics of ice in the shallow layers of the Antarctic ice cap and the rapidly increasing concentrations of greenhouse gases, primarily CO₂, across Antarctica in the given period of time.

2. Methods

Carbon dioxide levels in the atmosphere over Antarctica were obtained from the publicly available results of the CO₂ measurement station at the South Pole (90°0'0" S 0°0'0" W) and reported by the Scripps Institute of Oceanography [16] (Figure 1a). The data points correspond to monthly averages and date back to 1957. Meanwhile, concentrations of carbon monoxide (Figure 1b) and methane (Figure 1c) in the air over Antarctica have been measured since 1993 and 1986, respectively, at the Syowa station (69°0'15" S 39°34'55" E) by the Japanese Antarctic Research Expedition. Lastly, monthly averages of nitrous oxide (Figure 1d), yet another greenhouse gas, have been measured since 1997 at the South Pole by the US NOAA Global Monitoring Laboratory. The trends measured in Antarctica since 1957 mirror the global trends with respect to all the greenhouse gases considered here.

Four distinct determinants of the microstructure of surface and near-surface ice in Antarctica were chosen for the analysis: grain size, grain anisotropy, morphological irregularity and solidity. According to the Hall-Petch relationship, grain size is an essential factor defining the strength of ice and solid materials in general [17]. Reduced grain size, for example, leads to increased concentration of dislocations, which in the ductile regime act as obstacles to the movement of crystallites, resisting plastic deformation or fracture, whereas in the brittle regime they hinder the propagation path of cracks and cleavages, increasing, as a result, both the compressive [18] and the tensile [19] strength of ice. In addition, grain size affects the optical properties of ice, which determine how much sunlight the ice will trap and/or reflect. For example, by exerting an effect on the ratio between absorption and scattering, grain growth has been directly associated with reduced albedo, especially at near-infrared wavelengths [20,21]. Moreover, enlargement of the grains of ice decreases the spectral extinction coefficient and increases the shortwave radiation penetration [22], explaining why sunlight penetration is greater in coarse-grained ice and firn than in fine-grained snow [23]. At the same time, because of the greater exposed surface, finer grains generally tend to exhibit a greater solubility. Permeability to water, the inflow of which is intimately associated with melting, for example, is inversely proportional to the grain size of ice [24].

The aspect ratio as the measure of geometric anisotropy and the degree of elongation of grains is another important factor, first because it determines the density of packing [25] and, thus, the strength of ice, but also because it has an intrinsic effect on the optical properties. Namely, the optically effective grain radius is proportional to $3V/S$, where V/S is the volume-to-surface ratio, the reason being that the ratio of absorption to scattering is a function of the average distance the photons must traverse through the ice between

successive opportunities for scattering at the air-crystal interface [26], which is markedly different for two samples with an identical average grain size but different grain aspect ratios. This effectively means that a sample of ice determined to have the grain size of, say, 5 mm as its longest dimension during microscopic analyses or by sieving might have the optically effective grain diameter of a fraction of a millimeter if it only happened that the grains are plate-shaped.

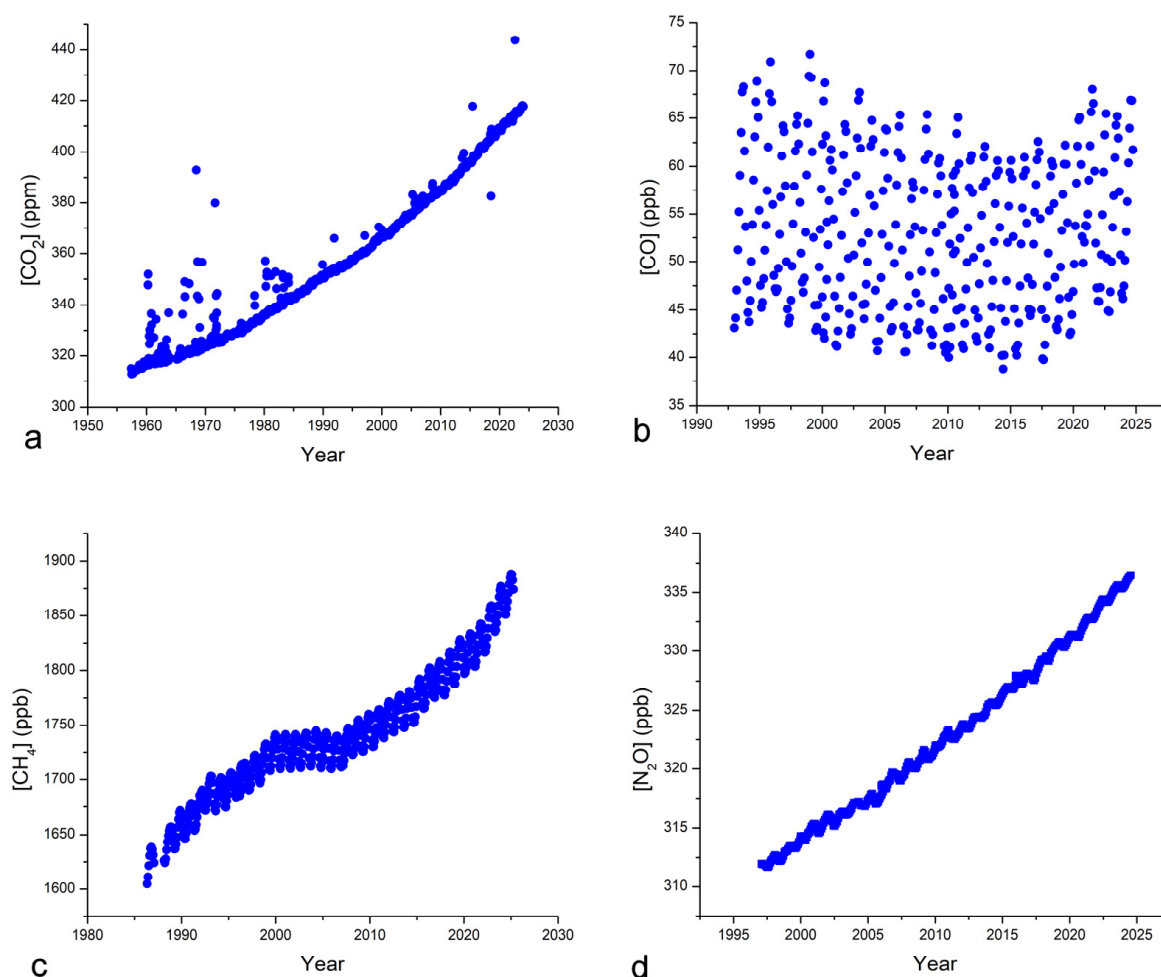


Figure 1. (a) Merged in situ and flask data for averaged monthly atmospheric CO₂ concentrations measured since 1957 by the Scripps Institute of Oceanography station at the South Pole (90°0′0″ S 0°0′0″ W). Data retrieved from https://scrippsco2.ucsd.edu/data/atmospheric_co2/spo.html (accessed on 12 February 2025). Monthly averages of flask atmospheric concentrations of (b) CO and (c) CH₄ in the Antarctic air, as measured by the Japanese Antarctic Research Expedition at the Syowa station (69°0′15″ S 39°34′55″ E). Data retrieved from <https://gml.noaa.gov/data/dataset.php?item=syo-co-flask-month> and <https://gml.noaa.gov/data/dataset.php?item=syo-ch4-flask-month> (accessed on 18 February 2025). (d) Monthly averages of N₂O flask measurements at the South Pole (90°0′0″ S 0°0′0″ W), as reported by the NOAA Global Monitoring Laboratory. Data retrieved from <https://gml.noaa.gov/data/dataset.php?item=spo-n2o-flask-month> (accessed on 18 February 2025).

The third morphological characteristic analyzed is shape irregularity, which is expressed here as the inverse of circularity. This irregularity, correspondingly, expresses the degree to which the elementary unit of snow, namely an ice crystallite, deviates from circle as the perfect geometric shape. Grains possessing uneven edges, indentations or protrusions would, according to this measure, have a high level of morphological irregularity. For the fourth and the final microstructural characteristic analyzed, triple junction angle was

the first candidate, given that this structural feature has been shown to influence climate signal preservation in polar ice [27]. Moreover, many impurities, such as sulfuric acid, were shown to segregate at triple junctions of Antarctic ice [28], potentially affecting its solubility. However, since it was imperative that the focus here be on recent icy precipitates, for which dense packing of grains is a rare phenomenon, this parameter had to be discarded. Instead, solidity of grains, as another morphological metric, was instated. Unlike extent, which is defined as the area occupied by the grain divided by the smallest rectangle fitting it, solidity, also known as compactness, equals the area occupied by the grain divided by the convex hull area. Solidity can be perceived as one of many possible geometric measures of structural order embodied by a particle.

The literature sources from which the information on one or more of these four characteristics was reported or where data were reported, such as optical or electron micrographs, from which these four characteristics could be calculated are listed in Table 1. To deduce parameters such as grain aspect ratio, circularity or solidity, image processing was carried out in ImageJ 1.53k (NIH, Bethesda, MD, USA). In some cases, other physical properties were used to derive the grain size, two of which were air permeability and specific surface area, which can be used to deduce the particle diameter given the known porosity, P , and particle sphericity, ϕ , using the following equations [29]:

$$k = \frac{1}{150} \frac{P^3}{(1-P)^2} \frac{(\Phi d)^2}{\mu} \quad (1)$$

$$S = \frac{6(1-P)}{\rho d} \quad (2)$$

$$k = \frac{1}{4.17\mu} \frac{P^3}{(S\rho)^2} \quad (3)$$

where k is the air permeability [(m/s)/(Pa/m)], S the specific surface area (m²/kg), ρ the snow density (kg/m³), d the particle diameter [m], and μ the viscosity of air (1.67×10^{-5} N·s/m² at -10 °C). Plotting of the microstructural data points as the function of the time of sampling was performed in Origin Pro 8.5 (OriginLab, Northampton, MA, USA). Linear regression fits and corresponding ANOVA statistical analyses were performed in the same software package. To calculate p -values, GraphPad 10.6.1 software (Dotmatics, San Diego, CA, USA) was used in conjunction with Microsoft Excel 2016.

Table 1. Literature sources of the micrographs and/or other microstructural parameters of Antarctic surface ice analyzed and the accompanying information pertaining to the original sampling sites, dates and depths. Superscripted asterisk denotes extrapolated depth.

Year of Sampling	Authors [Ref.]	Location	Coordinates	Altitude (masl)	Depth (m)
2020	Lu et al. [30]	Dålk Glacier, East Antarctica	69°24'0'' S 76°20'0'' E	139–161	0.035
2019	MacDonell et al. [31]	Müller Ice Shelf	67°14'0'' S 66°52'0'' W	19	0.6
2019	Skatulla et al. [32]	Good Hope Line Transect	58°8'16'' S 0°0'16'' W	0	0.05
2019	Wang et al. [33]	Prydz Bay	69°12'0'' S 76°18'0'' E	0	0.15
2019	Johnson et al. [34]	Southern Ocean	50°0'0'' S 0°0'0'' W–90°0'0'' S 360°0'0'' W	0	0.55
2018	Thomas et al. [35]	Priestley Glacier, Terra Nova Bay	74°20'0'' S 163°22'0'' E	80–2200	2.4

Table 1. Cont.

Year of Sampling	Authors [Ref.]	Location	Coordinates	Altitude (masl)	Depth (m)
2017	Inoue et al. [36]	Dome Fuji, Queen Maud Land	77°47'17" S 39°3'14" E	3764	0.1
2015	Moser et al. [37]	Kohnen Station, Dronning Maud Land	75°0'0" S 0°4'0" E	2892	0.1
2015	Bolshunov et al. [38]	Vostok Station Area	78°27'50" S 106°50' E	3488	0.5
2014	Carlsen et al. [39]	Kohnen Station	75°0'0" S 0°4'0" E	2892	0
2012	Calonne et al. [40]	Point Barnola, Central East Antarctica	75°42'0" S 123°15'0" E	3236	0.2
2012	Proksch et al. [41]	Kohnen Station	75°0'0" S 0°7'0" E	2892	0.015
2011	Dadic et al. [42]	Allan Hills	76°40'12" S 159°13'48" E	1600–2100	0.2
2010	Pirazzini et al. [43]	Aboa Station, Dronning Maud Land	73°3'0" S 13°25'0" W	200	0.2
2010	Lebedev et al. [44]	Alasheev Gulf	67°30'0" S 46°0'0" E	0	0.25
2009	Mahoney et al. [45]	McMurdo Sound	77°39'30" S 165°0'0" E	10	0.05
2009	Gallet et al. [46]	Dome C	75°6'0" S 123°21'0" E	3233	0.01
2008	Gallet et al. [47]	Dome C	75°6'0" S 123°21'0" E	3233	0.02
2007	Fujita et al. [48]	Dome Fuji	77°19'0" S 39°40'0" E	3800	0–12.4
2007	Dempsey et al. [49]	McMurdo Sound	77°39'30" S 165°0'0" E	10	0.55
2007	Saruya et al. [50]	Dome Fuji	77°19'0" S 39°42'0" E	3800	0.5
2006	Freitag et al. [51]	Kohnen Station	75°0'0" S 0°8'0" E	2892	1
2006	Brucker et al. [52]	Dome C	75°6'0" S 123°21'0" E	3240	0.1
2005	Alencar et al. [53]	Joinville Island	63°15'18" S 55°38'21" W	565 & 454	0.02
2003	Tang et al. [54]	Nella Fjord	69°22'0" S 76°20'0" E		0.1
2002	Kärkäs et al. [55]	Riiser-Larsen ice shelf, Dronning Maud Land	72°32'0" S 16°34'0" W W–74°59'54" S 10°0'30" W	30–2550	1.5
2000	Rasmus et al. [56]	Amundsenisen, Högisen and Kvitkuven	72°32'0" S 16°34'0" W W–74°59'54" S 10°0'30" W	40–2550	1.5
2000	Gow et al. [57]	Byrd Station Area	80°0'0" S 120°0'0" W	935–1843	1–5
1999	Albert et al. [58]	Siple Dome	81°39'0" S 148°48'36" W	730	0.1
1997	Gay et al. [59]	Terra Nova Bay, Dumont d'Urville and Talos Dome	68°36'0" S 137°43'12" E E–75°9'36" S 123°13'48" E	600–3470	0.08
1995	Haas et al. [60]	Bellingshausen, Amundsen & Weddell Seas	68°0'0" S 20°0'0" W W–78°0'0" S 125°0'0" W	0	0.05
1995	Massom et al. [61]	Indian & Western Pacific Oceans	60°0'0" S 138°0'0" E E–90°0'0" 142°0'0" E	0	0
1994	Cagnati [62]	Terra Nova Bay Region	74°42' S 164°8' E	0–2960	0.05
1994	Haas et al. [63]	Weddell Sea	70°0'0" S 60°0'0" W W–78°0'0" S 20°0'0" W	0	0
1994	Sturm et al. [64]	Bellingshausen, Amundsen & Ross Seas	68°0'0" S 109°0'0" W W–78°0'0" S 171°0'0" W	0	0
1993	Watanabe et al. [65]	Dome Fiji	77°19'0" S 39°40'0" E	3810	0.8

Table 1. Cont.

Year of Sampling	Authors [Ref.]	Location	Coordinates	Altitude (masl)	Depth (m)
1993	Worby & Massom [66]	Indian & Western Pacific Oceans	60°0'0'' S 139°0'0''–90°0'0'' S 141°0'0'' E & 60°0'0'' S 144°0'0''–90°0'0'' S 150°0'0'' E &	0	0
1992	Massom et al. [67]	Weddell Sea	70°0'0'' S 60°0'0'' W–78°0'0'' S 20°0'0'' W	0	0
1992	Jeffries et al. [68]	Ross Sea, Amundsen Sea and Bellingshausen Sea	68°0'0'' S 57°0'0'' W–78°0'0'' S 160°0'0'' W	0	0.19
1992	Walden et al. [69]	Amundsen-Scott South Pole Station	90°0'0'' S 45°0'0'' E	2804	0
1992	Veazey et al. [70]	McMurdo Sound and Pine Island Bay	77°52'35'' S 166°45'47'' E & 74°38'45'' S 102°17'46'' W	≤10	0.18 and 0.27
1992	Iwai [71]	Syowa Station	69°00'15'' S 39°34'55'' E	18	0
1991	Jeffries & Weeks [72]	Ross Sea (Balleny Islands to Terra Nova Bay)	71°17'0'' S 170°14'0'' E	0	0.027
1989	Konishi et al. [73]	Syowa Station	69°00'15'' S 39°34'55'' E	18	0
1988	Hatanaka et al. [74]	Syowa Station	69°00'15'' S 39°34'55'' E		
1986	Tison et al. [75]	Breid Bay	70°13'0'' S 23°47'0'' E	0	0.28
1985	Alley & Bentley [76]	Siple Coast	83°28'4'' S 138°5'49'' W	335	0.1
1984	Nishimura & Maeno [29]	Mizuho Plateau, East Antarctica	71°30'0'' S 39°0'0'' E	2230	0.5
1984	Dahe et al. [77]	Law Dome & Casey Station, Wilkes Land	66°16'5'' S 110°31'3'' E	359	0.1
1984	Urabe & Inoue [78]	Ongul Strait, Lutzow-Holm Bay	69°1'0'' S 39°35'0'' E	0	0.15
1983	Lange [79]	Weddell Sea	70°0'0'' S 172°0'0'' E–78°0'0'' S 60°0'0'' W	0	0.4
1979	Wada & Gonda [80]	Mizuho Station, East Antarctica	70°41'57'' S 44°16'45'' E	2230	0
1978	Duval & Lorius [81]	Dome C	74°39'0'' S 124°10'0'' E	3240	0*
1978	Ohtake [82]	Amundsen-Scott South Pole Station	90°0'0'' S 45°0'0'' E	2804	0
1977	Iwai [83]	Syowa Station	69°00'15'' S 39°34'55'' E	18	0
1975	Kikuchi & Hogan [84]	Amundsen-Scott South Pole Station	90°0'0'' S 45°0'0'' E	2804	0
1974	Hogan [85]	Amundsen-Scott South Pole Station	90°0'0'' S 45°0'0'' E	2804	0.003
1966	Paige [86]	Hut Point Peninsula, McMurdo Sound	77°47'0'' S 166°51'0'' E	143	0.50
1961	Shimizu [87]	Byrd Station	80°0'0'' S 120°0'0'' W	1553	0

The search for literature sources proceeded manually, using various combinations of keywords such as “ice”, “snow”, “crystal”, “grain”, and “Antarctica”. The keywords

were inputted in scientific paper databases including Google Scholar, Scopus and Web of Science. Every journal article, preprint, technical report and academic thesis that satisfied these keywords was downloaded, read by the author and manually extracted for relevant parameters descriptive of the microstructure of ice. Every source reporting directly or indirectly on any of the four microstructural characteristics of interest at acceptable locations and depths of the ice cap was ascribed an equal level of reliability and used as such. No assistance by any computational algorithms in detection and extraction of relevant data was used. Neither was any assistance of this kind utilized in the data processing, interpretation or presentation phases of this purely curiosity-driven project. Concretely, no computer models, including generative AI algorithms, were used as an aid in conceptualization, data mining, collection, analysis, interpretation, visualization or writing stages of this study.

3. Results

According to the global trends in concentration of atmospheric greenhouse gases, the levels of CO₂, CH₄ and N₂O have been continuously on the rise since the mid-20th century [88]. In contrast, the concentration of CO has been spiking sporadically, but also regionally, being tied to local sources of pollution, explaining four orders of magnitude lower concentrations of this gas compared to CO₂ over Antarctica (Figure 1). Unlike CO₂, which is atmospherically stable, CO is significantly more short-lived, as it tends to recombine with hydroxyl radicals abundant in regions of high water vapor and form CO₂, having lifespan of 1 to 3 months on average, as compared to the order of hundreds of years for a single CO₂ molecule [89]. In addition to this, CO₂ is also 50 times more soluble in water than CO (1.3 mg/g vs. 0.027 mg/g at 20 °C), which is another reason why the effect of CO₂ on crystallization of ice is expected to be significantly higher than that of CO, even at hypothetically identical exposures. Overall, out of these four correlations established between concentrations of greenhouse gases over Antarctica and time, three demonstrate a definite monotonous trend (CO₂, CH₄, N₂O), while one represents a completely random scatter (CO). When searching for trends at the level of grain microstructure, these two disparate categories of cases present guidance as to how an ideal correlation and a complete lack thereof would look like.

Changes in microstructural parameters descriptive of the size and morphology of ice crystals over the past 70 years, as established through the analysis reported here, are shown in Figure 2. The strongest correlation among the four parameters analyzed was for the grain size of surface or near-surface ice as the function of time of its sampling between 1961 and 2020. The grain size, namely, is shown to have been steadily increasing throughout the given period of time (Figure 2a). Averaging at around 0.22, 0.50 and 0.90 mm in the 1960s, 1970s and 1980s, respectively, it rose to 1.27, 1.08 and 1.46 mm in the 1990s, 2000s and 2010s (Figure 2b). Or, put differently, the grain size rose from an average of 0.57 mm in the 1960s, 1970s and 1980s combined to 1.29 mm in the period extending from 1990 to date. In contrast to the grain size, which increased over time, the grain aspect ratio (Figure 2c) and the grain solidity (Figure 2g) decreased. The magnitude of these changes was similar for the grain size and the aspect ratio, as illustrated by similar slopes of these values as functions of time, namely 0.024 ± 0.008 and -0.015 ± 0.006 , respectively. Or, more specifically, the grain aspect ratio decreased from 2.27 in the 1960s, 1970s and 1980s combined to 2.00 in the 1990s to 1.72 in the 21st century (Figure 2d). The change of the grain solidity, on the other hand, was much less pronounced, given an order of magnitude lower slope of -0.001700 ± 0.000007 . Meanwhile, the inverse of circularity as a measure of grain irregularity preserved near constancy throughout the six decades analyzed, decreasing to an insignificant extent (Figure 2e), with the slope of $-3.079 \times 10^{-4} \pm 0.003 \times 10^{-4}$ and the caveat that two notable waves were discerned, one peaking in the 1960s and another in the 1990s (Figure 2f), both of which were followed by two decades long periods when

the circularity of detected grains was significantly higher. In all, although nothing can be concluded about causation in the relationship between (i) the steady rise of atmospheric CO₂ (Figure 1a) and two other greenhouse gases analyzed, namely methane (Figure 1c) and nitric oxide (Figure 1d), and (ii) the changes in primarily the grain size (Figure 2a) and the aspect ratio (Figure 2c), but also to some extent the grain solidity (Figure 2g), there exists a clear correlation between them.

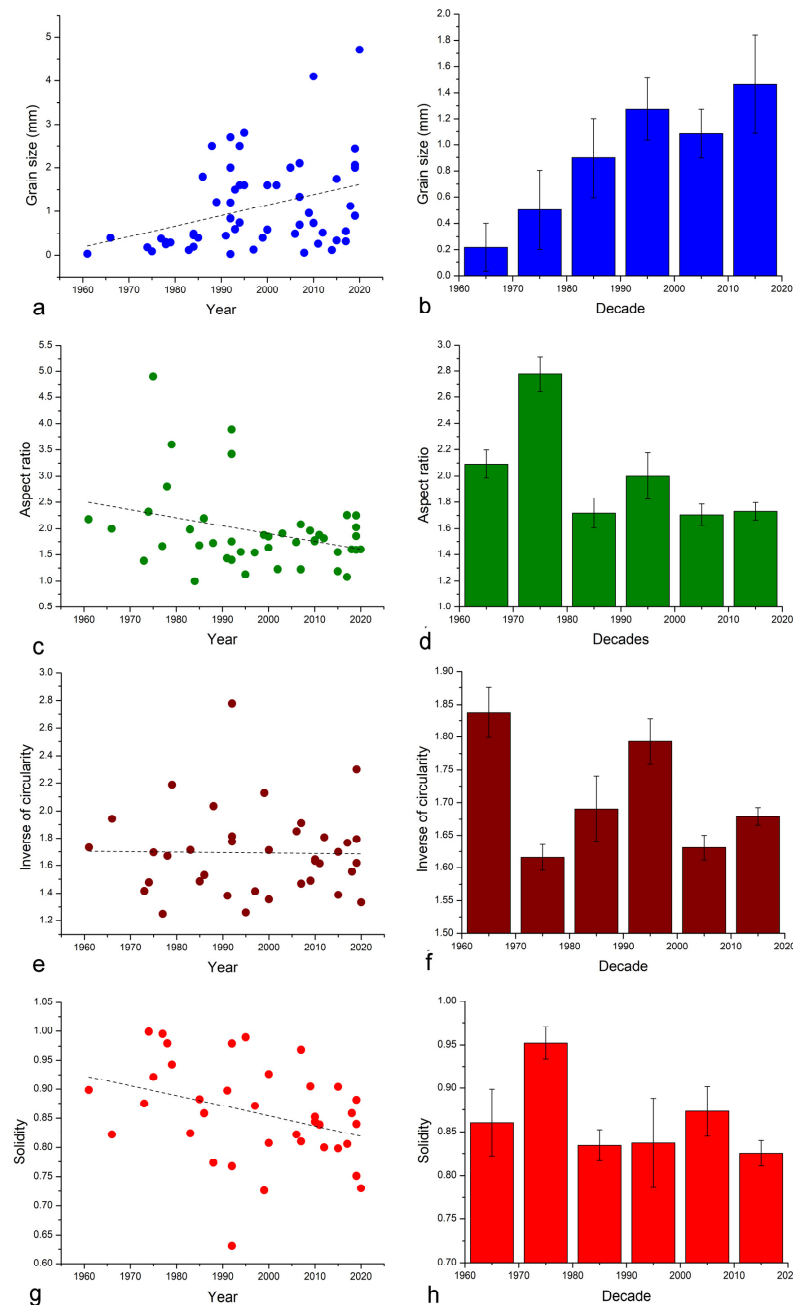


Figure 2. Average grain size (a,b), grain aspect ratio (c,d), grain irregularity expressed as the inverse of circularity (e,f), and grain solidity (g,h) of surface or near-surface Antarctic snow or firn as a function of the year (a,c,e,g) or decade (b,d,f,h) of their sampling. Each data point in (a,c,e,g) corresponds to an average extracted from an individual literature source referred to in Table 1. Linear fits reflect the overall trends followed by the respective microstructure parameters over time. Data normalized to decades on which the surface or near-surface Antarctic snow or firn were sampled are represented as averages of no less than 2 (1960s) and no more than 15 (1990s), 14 (2010s), 12 (2010s) and 12 (2010s) measurements in (b), (d), (f) and (h), respectively. Error bars in (b), (d), (f) and (h) represent standard errors of the mean.

From the statistical standpoint, the linear regressions of the four trends analyzed yielded distinct significance regimes, with the Pearson correlation coefficient of 0.34657 and adjusted R-square value of 0.10402 measured for the grain size fit; -0.32448 and 0.08398 for the aspect ratio fit; -0.01666 and -0.02829 for the inverse circularity fit; and -0.3474 and 0.09556 for the solidity fit. These weak to moderate levels of strength and direction of the linear relationship between the variables, however, become offset by the comparatively large sample sizes. Correspondingly, given the F value of 7.50806 , DF_n (number of predictors) of 1 and DF_d (residual degrees of freedom) of 55, the p value, derived from the ANOVA F-test, for the grain size linear regression fit was calculated to be 0.0083 , which is in the range of considerable statistical significance. As for the aspect ratio linear regression, with the F value of 4.94241 , DF_n of 1 and DF_d of 42, the p value, derived from the ANOVA F-test, was calculated to be 0.0316 , which is in the range of conventional statistical significance. As for the inverse circularity linear regression, with the F value of 0.00972 , DF_n of 1 and DF_d of 35, the p value, derived from the ANOVA F-test, was calculated to be 0.9920 , which is considered not to be statistically significant. And lastly, for the solidity linear regression, with the F value of 4.80365 , DF_n of 1 and DF_d of 35, the p value, derived from the ANOVA F-test, was calculated to be 0.0351 , which is, as in the case of the trend in the grain aspect ratio, in the range of conventional statistical significance. These results attest to the statistical reliability of the trends observed here, especially for the grain size ($p < 0.01$), but also for the grain solidity ($p < 0.05$) and the grain aspect ratio ($p < 0.05$). In contrast, no change in the inverse of circularity ($p = 0.99$) can be pinpointed, neither by naked eye observations nor the ensuing statistics.

4. Discussion

4.1. Mechanism and Implications

If the correlation between (i) the steadily rising atmospheric concentrations of CO_2 and other greenhouse gases, both globally and over Antarctica (Figure 1), and (ii) the increase in the grain size (Figure 2a,b) and the decrease in the aspect ratio (Figure 2c,d) and solidity (Figure 2g,h) of surface and near-surface ice in Antarctica during the six decades analyzed here does amount to causation, it is worth discussing the possible mechanistic aspects of it and environmental consequences. The results presented in this study stem from an unbiased quantitative analysis of data extracted from a variety of literature reports; however, to provide a deeper exploration of potential mechanisms underlying the observed correlations, it is imperative that the discussion delves sporadically into speculative territories. This speculative aspect is an intentional effort to stimulate further investigation and enrich the understanding of evidently complex relationships at work, even as these interpretations remain subject to additional validation.

Initially, it was hypothesized that if increased levels of CO_2 are able to affect the crystallinity of ice, the effect should be destructive. From the materials chemistry standpoint, CO_2 can disrupt the crystallization of ice by weakening the hydrogen bonds between water molecules within the ice crystal structure, leading to a less robust ice with increased susceptibility to fracture and melting. Essentially, CO_2 may be expected to make ice weaker and more prone to breaking apart, especially when present in significant quantities within the ice matrix. Simulations, for example, have shown that ice that has been infiltrated with CO_2 to the point when the gas occupies 2% of its volume is roughly 38% less strong than CO_2 -free ice [90]. Also, when CO_2 is trapped as gas bubbles within ice, these bubbles can act as nucleation sites for further ice crystal formation, potentially affecting the crystal morphology. Segregating along triple junctions and other grain boundary regions, bubbles, moreover, act as pinning points [91], impeding the propagation of dislocations and hindering the grain growth during crystallization. Hence, one of the starting hypotheses was that

more CO₂ in the atmosphere would cause ice grains to be smaller and also more disordered. Carbon dioxide gas inclusion during freezing of water [92] and a range of different aqueous systems [93–95], further, has been shown to reduce supercooling required for nucleation to occur, presumably because of the ability of the bubbles or the gas–liquid interface to act as a surface promoting heterogeneous nucleation [96]. As a result of this, it has become a regular practice in the food industry to add CO₂ gas bubbles to promote freezing of a range of items, including, most notably, ice cream [97]. Given the inverse relationship between the nucleation rate and the grain size [98], this nucleation-promoting effect of CO₂, as it was initially hypothesized, should further contribute to the diminishment of the crystallinity of ice.

An additional factor is the effect of CO₂ dissolved in the form of carbonate, H_xCO₃^{x−2} (x = 0 or 1) ions. Although ocean waters bordering Antarctica have exhibited stable alkalinity and concentrations of dissolved inorganic carbon, both averaging at around 2100 ppm [99], since 1993, crystallization of water that gets deposited in the solid form over the ice caps begins in the air, which does not have the buffering capacity of oceans. Even though crystallization of ice proceeds via condensation [100], not precipitation, the effects of CO₂ in the air and carbonate species present within the pockets of liquid water trapped on the surface and in the interior of the snowflakes, the firm and the ice on their crystallization and metamorphism must be pronounced. In general, by altering speciation, interfacial layer composition and intermolecular bonding, reduction in the pH of a solution containing crystal growth units can have a dramatic effect on the crystallization reaction. Morphology and other microstructural parameters of a range of different materials often-times dramatically change in response to changes in the pH of the solution during their synthesis [101–104]. Properties of materials fabricated under such different pH conditions can also be subject to considerable changes, as exemplified by the case where pH was able to control the diameter of heterostructured Pd/PdO nanowires [105] and, in consequence, their capacity for the electroreduction of CO₂. As for pure water, increasing the ionic strength of water suppresses its freezing point, making such ice, conversely, more prone to melting relative to pure water. All these arguments suggest that the elevated global concentrations of CO₂ should have a definite effect on the crystallization of ice in Antarctica. Even at moderate concentration changes as those observed in the past 100 years atmospherically, amounting to circa 130 ppm [106], the effect of these changes on the microstructure of ice and its physicochemical stability might be significant.

The idea that CO₂ might make ice grains smaller by interfering with hydrogen bonding, however, is not supported given the evidenced increase in the size of ice grains paralleling the increase in the atmospheric concentration of CO₂ and two other greenhouse gases over Antarctica. Moreover, the fact that the increase in the grain size was paralleled by a drop in the solidity of the grains and in their aspect ratio suggests that the crystal growth proceeded more hastily than normally. A speedier growth at a steady nucleation rate typically produces larger crystals with a less refined morphology, which in this case corresponds to more isotropic, rounded shapes in lieu of elongated ones. Simultaneously, the solidity of shapes becomes sacrificed due to the greater degree of stochastics governing crystal growth and transformations. This accelerated growth effect is supposed to be exhibited in the formative stages in the lifetime of a snow crystal, in the air, although the possibility of metamorphic effects on the icy Antarctic floor cannot be discarded either.

Because of the comparatively dry air in which they form, snow crystals in Antarctica grow slower and into lower sizes than elsewhere on the globe [107]. Snow crystals forming under such conditions are typically prismatic, whereas an accelerated growth promotes dendritic branching and the rise of more isotropic or even plate-like morphologies. The latter type of crystals is usually found in climates more humid and hospitable than in Antarctica, and can have as much as a couple of millimeters in length. If CO₂ does affect

ice crystal growth, the effect can be direct or indirect. For example, CO₂ has warmed the atmosphere, but higher temperatures typically slow down the ice crystal growth and may be expected to lead to a more controlled, uniaxial growth and a lesser degree of branching. Water, however, is anomalous at innumerable levels and its crystallization by condensation partly disobeys these common principles. In fact, according to the snowflake morphology diagram first constructed in the 1930s by Nakaya [108], prismatic crystals forming at very low temperatures and low humidities, such as those typifying the air over Antarctica may transition to flatter and larger prisms or platelets as temperature increases, only at even higher temperatures to revert to extreme uniaxial morphologies [109]. Further, if dislocations and other lattice defects pose a critical limit with regard to how large crystals can grow, then even slightly elevated temperatures may lead to a more controlled growth, producing a lesser concentration of defects and allowing the crystals to grow to effectively larger sizes. Higher temperatures, moreover, can promote partial melting of snowflakes as they fall through the air, which would round the icy particles and make them more prone to metamorphosis and sintering on the ground. CO₂ can also affect the airborne moisture by trapping heat and increasing water evaporation, which is another means by which this gas can accelerate the growth of ice crystals in the air. As for direct effects, they are less likely, especially given the generally detrimental effect of CO₂ on formation of particles via condensation [110]. CO₂, specifically, introduces stochastic disorder in the supersaturation distribution of water vapor by altering thermal and mass diffusivities of the molecular growth units. This effect can explain the rounding and loss of solidity of particles, but not the enhanced growth of crystalline grains, which is why indirect effects are most likely to be responsible for the observed changes in the grain size and other morphological parameters.

The environmental repercussions of the microstructural effects reported here can be considerable. If CO₂ induces the enlargement of the ice crystals, it also renders them less soluble, simply because solubility of ice and materials in general—like many forms of their physicochemical reactivity as well—is proportional to their surface-to-volume ratio. If so, then elevated atmospheric concentrations of CO₂ may halt the melting of the Antarctic ice cap and achieve a similar mitigation of Earth's climatic imbalances as that seen at work when excess CO₂ in the air is consumed by plants, fostering their growth and producing, via photosynthesis, more oxygen.

The opposite scenario, however, is more probable if the effect of the enlargement of crystalline grains of ice on the optical properties of polar snow is considered. Coarser ice grains, namely, exhibit reduced albedo and are more prone to absorb sunlight radiation and undergo melting. If the optical effects prove to be more decisive than the solubility effects, then the destabilization of the system may occur, where the increased concentrations of CO₂ would make ice more prone to melting due to its indirect effect on the microstructure of ice, whereas the melting of this coarser snow would expose the underlying firn and ice with an even lower albedo and even coarser grains, leading to a potential runaway effect and even faster disappearance of the polar ice cap than that evident today [111]. Additionally, some element of disorder introduced to the microstructure of ice, evident from the reductions in solidity and morphological anisotropy, may also be a factor facilitating the weakening of ice and its propensity for melting. As it frequently happens during analyses of environmental effects, the nonlinear, autopoietic, feedback-looped complexity of the biosphere ensures that any conclusions pertaining to the global effects of certain chemicals, procedures or events remain ambiguous.

4.2. Study Justification and Limitations

Crystallization of water in even the most controlled laboratory environments presents an extraordinarily complex physicochemical phenomenon from which a number of anoma-

lies emanate [112]. When this phase transition occurs via condensation of water vapor in the troposphere and crystallization and recrystallization continue as the snowflakes fall through the air and for years after they touch the ground, transitioning to loose firn first and then to increasingly compact and pore-free ice, then a number of chemical and environmental factors come to influence the outcome of this process, complicating any effort to establish a correlation between the final product and any given parameters affecting this process. Because of this interplay of a variety of factors determining the morphology of surface and near-surface ice crystals, it is logical that the correlations applying to this morphology and shown in Figure 2 are nowhere as clean as those applying to greenhouse gases over Antarctica and presented in Figure 1. Still, the assumption underscoring this study was that if a large enough dataset was collected from all the possible literature sources since the microstructural parameters of snow and ice had begun to be measured with a sophisticated level of precision, some correlation might be possible to obtain. To minimize this rather large range of variability, a number of prerequisites were implemented in the data selection stage, including, most critically, the depth from which ice samples were retrieved, which was limited in all but seven cases—in which it was either indicated that the morphology was highly similar to that of the near-surface deposits or data were extrapolated with a reasonable degree of confidence to the surface level—to less than 60 cm. The grain size of ice increases steadily with depth due to sintering [113], at the reported rate of ~3 mm per year [114], while the microstructure of ice grains at different depths of the Antarctic ice cap reflects the climatological characteristics of the geological eras in which they formed. For example, the size of grains comprising glacial ice is lower than that comprising interglacial ice [115,116], possibly because of the effects impurities and soluble shape modifiers exerted by dragging and pinning at the grain boundaries during crystal growth [117,118]. To reduce this depth effect, the only information used in the data collection stage was that on crystals of snow or firn sampled from depths lower than 60 cm or those whose size could be confidently extrapolated down to the surface value.

Sampling out surface or near-surface Antarctic ice, however, comes with challenges that extend beyond the logistical and operational and into the basic scientific. First, it is known that Antarctic glaciochemistry exhibits a very broad seasonal variability [119–121], for which reason it is recommended that any analyses utilize annual or multi-year averages, if not specifically and systematically dated for seasonal investigations. Also, the distance from the ocean is a pronounced determinant of the ionic content in the ice, which itself is a strong determinant of the ice crystal forms, but so is the elevation. Hence, as one moves inland across the Antarctic Peninsula towards the Ronne Ice Shelf in West Antarctica or from the coast of Mirnyy in East Antarctica deeper into the Wilhelm II Land, the concentrations of sodium and chloride in ice decrease and increase, respectively, within the rather broad, 5 to 15,000 ppb range [122]. At the same time, as elevation from which the surface snow is sampled increases, the concentration of both of these ions drop, unlike that of species such as sulfate, sulfonate or nitrate, simply because the deposition of the ice crystals at low elevations, near the sea level, occurs in the presence of sea salt, with insignificant aerosol loss or accretion in the post-depositional stage. Because of this interplay of mutually dependent variables, the net result of the two effects is difficult to predict. Multi-year analyses, like the one employed here, while challenging, can help mitigate these complexities by averaging out seasonal and spatial variations, providing conditions for a more robust assessment of long-term trends.

Literature sources in this meta-analysis were broadly distributed, covering all relevant reports published in the period from the mid-1950s to today. Additionally, climate conditions represent the key determinants of the size and shape of the initially formed snow crystals [123]. Therefore, to minimize seasonal variability, mostly samples collected

during the austral summers were considered and only occasionally those acquired at springtime. Although one study concluded that the difference between precipitation and evaporation is between 100 and 200 mm for every month in Antarctica [124], and another study found that there is twice more precipitation in the snowiest month of June than in the least snowy month of December, there is still over 15 mm/month precipitation in the latter month [125,126], meaning that there is snow falling on Antarctica all year around, despite the fact that the net annual amount of precipitation is still within the domain of deserts on Earth. Still, the average air temperature changes with season, and temperature at the time of snow formation is usually determined by measuring the isotope ratios of HD^{16}O and H_2^{18}O relative to H_2^{16}O as proxies. The effect of the temperature gradient on snow fabric evolution is considerable [127,128] and can affect the distribution between the growths along the basal plane and along the prismatic plane, where the former drives the grains toward plate-shaped forms while the latter fosters the formation of columnar crystals. How significant these morphological differences are for the mechanical strength of ice is probably best illustrated by the fact that non-basal deformation of ice crystals, paralleling the prismatic or the pyramidal faces, requires a stress at least 60 times greater than that needed to induce a basal slip at the same strain rate [129], exemplifying a case of extreme mechanical anisotropy. The evidence that ground temperature changes responsible for crystal transformations commencing as soon as snowflakes touch the ground are not trivial comes from the fact that the snow temperature at the depth of 0.1 m is more or less constant from the beginning of May to mid-October, averaging at around -65°C , but then increasing to reach its peak of circa -35°C in mid to late January, after which it begins to drop again [130]. The approach pursued here is supported by prior studies performed in Antarctica [29], which have shown that neither density nor specific surface area of snow change consistently with temperature, meaning that the change in these properties with the first meter of depth is minimal and negligible. In addition, the strong winds over Antarctica ensure that diffusive mixing prevails over temperature effects on the microstructural parameters of snow [131], given that some snowflakes can cross vast distances from the point of their nucleation until they deposit on the ground [132], whereas vertical or even nearly vertical precipitation is very rare. Nevertheless, mostly samples of snow from depths lower than 60 cm were considered in the analyses, which can be higher [133] or within [134] the range of the measured thickness of snow in Antarctica, below which layers of firn and the glacial ice reside.

Humidity is another factor that can greatly influence the morphology of ice crystals, especially because these crystals are produced via condensation of water moisture, not precipitation from supersaturated and/or supercooled aqueous solutions. The higher moisture over the Arctic than over Antarctica explains the considerably larger size of crystallites forming snow and, eventually, ice in the Arctic than in Antarctica. In fact, when the first polar ice crystal size analyses were conducted, in the 1950s and the early 1960s, this discrepancy was obvious and compared to 0.902 mm obtained for the average grain size of the surface ice by, for example, Schwarzacher between 1955 and 1958 in the Arctic Ocean [135], Paige obtained a little over twice less, 0.4 mm, in McMurdo Sound in Antarctica in 1965 and 1966 [86]. On the other hand, because of the extreme drought and overall desert-like conditions present in Antarctica, the moisture demonstrates minimal seasonal or month-to-month variations, in the range between 61 and 67% for every month of the year [136,137], which is a positive factor facilitating the validity of the approach pursued in this study.

The fluffy crystals of ice, as they get deposited as snowfall onto the Antarctic permafrost, undergo various forms of metamorphism. One of them is equithermal, typically driven by wind that rolls the crystalline grains, smoothes and rounds them into a wind

slab (hence also called destructive metamorphism), building the bonding and increasing the strength of the material. Another type of metamorphism is temperature-gradient, where the insulating effect of the snow cover creates a positive temperature gradient proportional to the depth [138] and drives the upward convection of water vapor through the snowpack. Notably, this gradient is present only in the winter, when the ice caps grow, whereas in the summer, the gradient is negative, and in spring and autumn it can be absent [131]. Another factor driving this upward transport of water vapor may come from the theory distilled by Jožef Stefan as he studied phase transitions with moving boundaries in the context of crystallization of ice and remarked that the heat released by the exothermic recrystallization of ice in deep columns is being conducted completely through the ice and to the atmosphere [139], given the inability of ice to store heat [140]. These conditions favor crystal enlargement—hence also called constructive metamorphism—and the formation of more angular and faceted crystals. Here, pressure sintering and dislocation creep act as two dominant mechanisms of densification [141], which is also facilitated by the presence of quasi-liquid water lining up grain boundaries even in the densest and purest ice, explaining its perpetual slipperiness and stemming from the reduced hydrogen bonding by molecules at this interface, which induces molecular anharmonicity [142]. Thus, crystal anisotropy and overall morphology can significantly vary depending on the time of sampling, even for recent, relatively fresh snow. In addition, five out of six different types of snow in a single sample, namely new snow, recent snow, soft-moderate slab, hard slab and melt-grain clusters, usually have identical or nearly identical grain sizes—that is, all except depth hoar [64]. Additionally, for most ice columns, the average grain size remains more or less constant, in the 1–4 mm² range for the first kilometer of depth, after which it gradually increases, reaching values higher than 50 mm² at depths greater than 3 km [143]. Altitude, interestingly, does not present a critical factor, given that the mean thickness of unit layers within the upper 100 cm depth of surface snow is the same [144] at every altitude between 1000 and 4000 m, with no trend in this function being delineable.

Despite this, only surface and near-surface icy deposits were included in the analyses. Inclusion of ice core data would be impractical as such data would be difficult to relate to crystals precipitated in the past 60 years because of the considerable age discrepancy. For example, as one moves from moister west Antarctica to drier east Antarctica, the depth at which firn transforms to glacier ice shifts from two and three orders of magnitude in age, that is, from 10 to nearly 100 meters, which corresponds to deposition events within the window of between 100 and up to 2000 years. As for firn, the layer sandwiched between the surface snow and the deep ice, representing solid water with a slightly higher porosity than that of ice (20–30% vs. 20%, respectively), the structural changes it undergoes over time are also dependent on the local weather patterns, latitude and altitude. Effectively, this has left only the surface and subsurface snow, the least rigorously studied of all forms of solid water in Antarctica, with the porosity of typically 90%, to be assessed. For this reason, studies with multiple drilling sites were considered ideal as they allowed for averages to be derived and geographical location as a variable be minimized.

Another source of error must have come from the variability of methods used to measure the grain dimensions. Very often, especially in studies predating the use of low-temperature scanning electron microscopes [145], first used in the mid-1980s to analyze ice from Antarctica [146], the resolving power of the magnifying devices was insufficient to cover the entire distribution of grains and some grain sizes are likely to have been left undetected. Such was the case, for example, with a study where a videocassette recorder device coupled to a 640 × 480 pixel camera was used to measure the particle size [73]. One would expect that the advent of techniques for visualization of microscopic matter with an ever finer resolution during the six decades encompassed by this study would

create an obvious artifice in terms of a consistent reduction in the grain size detected over time, and yet the fact that the exact opposite was the case implicitly supports the validity of the findings presented here. In addition, early observations of Antarctic snow crystals conducted in the 1960s and early 1970s primarily focused on intriguingly long crystals of bullet-like and prism-like shapes, which would be another factor pushing the grain sizes to the higher end at the earliest time points covered by this study. In spite of this, these early temporal segments were characterized by the lowest grain sizes detected, indirectly validating the observed trends. In addition, global air pollution caused by the airborne particulate matter has been mostly on the rise throughout the last century [147] and is expected to have led to an increasing concentration of impurities in the Antarctic snow. These impurities are known to be present in polar ice [148], where they act as impediments to the grain boundary propagation during crystal growth [149], thus reducing the crystallinity of the material. However, as with the progress in analytics, the expected effect, namely the reduced grain size over time, is opposite from the observed, suggesting that it may not be present, let alone be decisive.

In the end, it cannot be overstated how the correlations derived here are subject to massive amounts of uncertainty. Given the immense variability of environmental conditions under which ice forms, observing the effects of comparatively subtle physical and chemical changes in the gaseous content of the atmosphere from which ice crystallizes and of metamorphic transformations it undergoes when brought into contact with the permafrost requires rigorous statistical analyses of very large sets of data. With the aid of more advanced computational methods and perhaps even artificial neural networks for processing, far larger datasets, possibly including the totality of all available publicly presented scientific information on snow and ice in Antarctica and in other arctic zones to date, could be analyzed, yielding more statistically reliable inferences than those of comparatively modest reliability reported here.

5. Conclusions

The present study set out to investigate whether global warming and elevated concentration of CO₂ and other greenhouse gases over the past 70 years have left the trace on the microstructure of ice deposited in Antarctica during this time. A systematic analysis of relevant data published in literature revealed a strong correlation between atmospheric CO₂ levels and changes in the microstructural characteristics of Antarctic surface ice from 1961 to 2020. The most pronounced trend was a steady increase in the grain size over time, rising from an average of 0.57 mm in the 1960s, 1970s and 1980s combined to 1.29 mm in the period from 1990 to date. In contrast, the grain aspect ratio and solidity exhibited a gradual decline, with the aspect ratio showing a change rate comparable to that of grain size, decreasing from 2.27 in the 1960s, 1970s and 1980s combined to 2.00 in the 1990s to 1.72 in the 21st century. While such trends provide a robust observation grounded in literature data, the underlying mechanisms driving these changes remain speculative owing to a lack of direct experimental evidence linking atmospheric compositional changes to the structural characteristics of polar ice.

This study has significant limitations, stemming from the inherent variability of environmental, spatial, and seasonal factors that influence snow and ice crystal morphology in Antarctica. Factors such as sampling depth, elevation, distance from the ocean, seasonal precipitation cycles, and atmospheric ion composition introduce substantial variabilities, making it difficult to isolate the direct effects of atmospheric CO₂. While stringent criteria for data selection were implemented to mitigate some of these confounding factors, the overall variability in sampling methods, geographical distribution and observational techniques employed across studies mitigate the precision of the correlations. Furthermore,

the methods used to measure the grain dimensions varied substantially over time, potentially introducing biases related to technological advancements in analytical techniques of relevance.

The findings of this study should therefore be viewed as a proof-of-concept rather than definitive conclusions. The combination of modest sample sizes, variability between datasets and reliance on indirect connections between greenhouse gas concentrations and ice morphology makes it imperative to distinguish robust observations from speculative interpretations. Future research should employ advanced computational tools, such as machine learning algorithms or artificial neural networks, to analyze far larger and more comprehensive datasets. Additionally, controlled experiments simulating CO₂ levels and their influence on snow crystal formation could help clarify the hypothesized mechanisms. Incorporating multi-year, geographically diverse datasets while employing methods to address spatial and seasonal variability will improve the reliability of observed correlations. Despite the inherent uncertainty in attributing microstructural changes directly to atmospheric greenhouse gas levels, the findings presented here offer a valuable framework for understanding long-term trends in ice morphology, which may contribute to systemic outcomes ranging from diminished ice stability to accelerated ice sheet disintegration to rising sea levels.

The findings reported here indicate a clear correlation between the rising levels of greenhouse gases and the evolution of ice microstructure. In the long term, these structural changes may provide a balancing mechanism for the planetary climate homeostasis, but may also contribute to the weakening of ice integrity. This would increase the susceptibility of ice to melting and fracturing, thus accelerating ice sheet disintegration and sea level rise. Given these potentially dire outcomes of physicochemical events starting at the atomic scale, the findings presented here stress out the need for further and more empirically and computationally elaborate investigation into the impact of atmospheric composition on ice stability. Antarctica currently houses the world's most advanced facilities for detecting neutrinos and other cosmic rays, and if similarly sophisticated infrastructure for studying the climatic changes occurring in ice caps on the atomic scale were to be established, answers to the questions raised by this study could potentially be answered in foreseeable future.

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