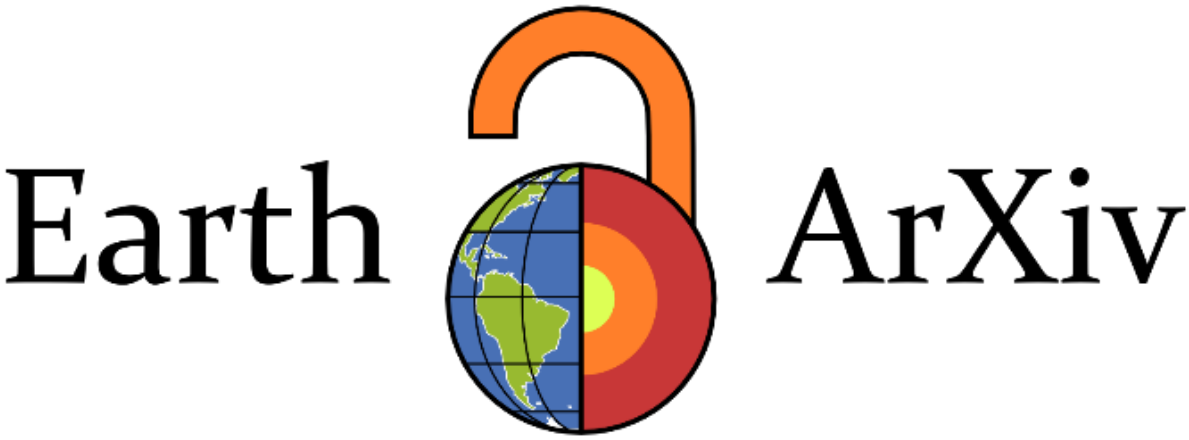

An Ice Core Snapshot of Past Atmospheric Chemistry in Mt. Everest's 'Death Zone'

Authors: Mariusz Potocki[1] Paul Andrew Mayewski[1]

Affiliation:

[1] Climate Change Institute, University of Maine

ABSTRACT.

We present a unique atmospheric chemistry record from the highest ice core ever recovered (8020 m, South Col Glacier (SCG), Mt. Everest), that captures ~400 years of deposition during the latter half of the first millennium BCE. Due to recent glacier thinning, the upper ~2000 years of accumulation have been lost, however, this is the only ice core record ever recovered from the "Death Zone (>8000 m)" and likely the only record that can be attained. Insights from this 10m deep record and comparison with an ice core we recovered on the north side of Mt. Everet include: an estimated lapse rate of water isotopes at extreme elevations; the influence of southerly and northerly source air masses on precipitation, dusts and overall atmospheric chemistry over Mt. Everest; and possibly the earliest influences of human activity on the chemistry of the atmosphere in this region.

INTRODUCTION

Glaciers around the world are retreating, and in the process, ice core archives that preserve records of past climate and atmospheric chemistry are being lost. High mountain glacier systems, particularly above 5000 meters, remain under-sampled despite their importance to regional water security and their sensitivity to atmospheric circulation and radiative balance. Within the Hindu Kush Himalaya lies the world's highest glacier, the South Col Glacier (SCG) on Mt. Everest (8020 m), an area rarely explored scientifically until recently.

The 2019 National Geographic/Rolex Perpetual Planet Mt. Everest Expedition conducted the most comprehensive scientific investigation of the Nepalese side of Everest to date, including meteorology, glaciology, biology, geology, and mapping (Mayewski et al., 2020). This effort resulted in the recovery of the highest ice core ever drilled—from SCG (Figures 1-3) and the installation of the two highest automatic weather stations on Earth (Matthews et al., 2020). The SCG ice core is located near the transition between the troposphere and stratosphere in the so-called "Death Zone," where oxygen levels are roughly one-third of those at sea level and only a few climbers have survived overnight.

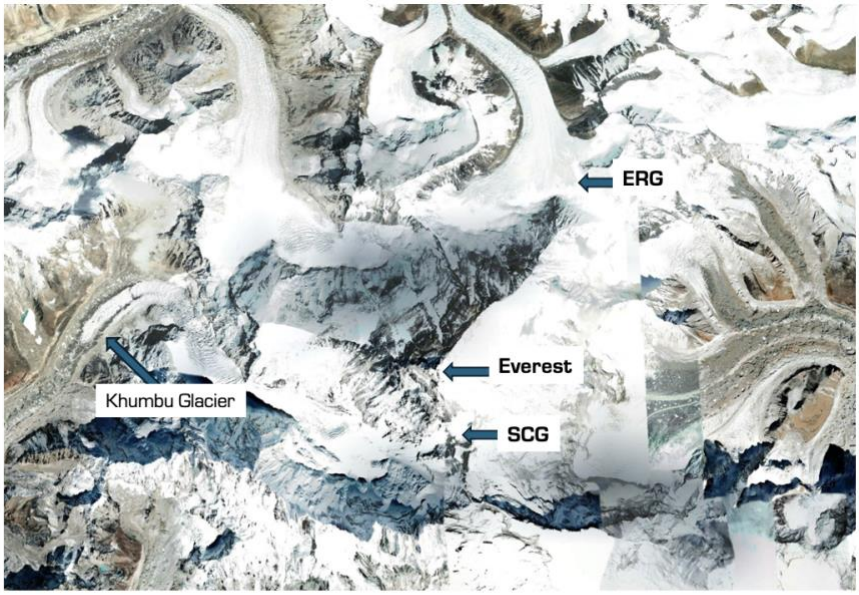

Figure 1. Location map showing Everest (summit), Khumbu Glacier (south side of Everest), SCG (South Col Glacier drill site, 8020 m), ERG (East Rongbuk Glacier drill site, 6518 m).

Figure 2. South Col Glacier camp and climbers ascending Mt. Everest. The ice core drill site is indicated by a red arrow. Picture by M. Potocki.

Figure 3. M. Potocki and Sherpa support team.
Picture by Dirk Collins, National Geographic.

Dating of ice on the surface of the 10-meter-deep SCG ice core reveals that, over recent decades, the upper ~2000 years of the record have been lost, exposing ancient ice at the surface (Potocki et al., 2022). Despite its relatively shallow depth, the SCG ice core offers a rare snapshot of atmospheric chemistry during the latter half of the first millennium BCE, capturing a ~400-year record based on annual layer counting and radiocarbon dating. The high sampling resolution used in this study allows for identification of patterns in stable water isotopes, soluble ions, and trace/rare earth elements preserved in the ice.

To provide regional and elevation-based perspective, we compare the SCG record with results from a previously recovered core from the East Rongbuk Glacier (ERG, Figure 1), located 6.5 km north of SCG and at a lower elevation (6518 m). The ERG ice core, analyzed by joint US-Chinese teams, covers the last ~1000 years and has provided insight into snow accumulation, dust transport, atmospheric circulation, and early anthropogenic signals (Kang et al., 2000, 2001; Hou et al., 2003; Kaspari et al., 2007, 2008, 2009a, 2009b, 2011; Zhang et al., 2003).

Our paper examines several key aspects of the SCG record: the isotope lapse rate between SCG and ERG (Yang et al., 2023), the influence of southerly monsoon source air masses on nitrate, ammonium, and marine ions (Mayewski et al., 1983, 1984), dust inputs from Tibetan and Indian source regions, and a possible early anthropogenic signal recorded in silver and cobalt, potentially linked to ancient mining in South Asia (Prasad, 1990; Craddock, 2014). These findings are of particular importance because SCG is likely to disappear in the coming decades due to continued glacier mass loss.

METHODS

The South Col Glacier (SCG) ice core was recovered in April–May 2019 during the National Geographic/Rolex Perpetual Planet Mt. Everest Expedition. The 10-meter-long core was drilled at 8020 m under extreme environmental and logistical conditions, hence the

relatively shallow depth. Following recovery, the core was carried by the Sherpa team from the drill site to Everest Base Camp, transported by helicopter to the U.S. Embassy in Kathmandu for freezer storage, and then shipped frozen to the Climate Change Institute (CCI) at the University of Maine.

The core was sampled using the CCI continuous melting system (Osterberg et al., 2006). A total of 966 continuous samples were collected at an average resolution of 1.04 cm and analyzed for major, trace, and rare earth elements, soluble ions, and stable water isotopes.

During the melting process, sample fractions from both the interior and exterior of the core were collected into discrete vials. The inner stream was used for elemental and ionic analyses, while the outer stream was reserved for stable isotope measurements. Major and trace element samples were acidified to a 1% solution using Optima-grade nitric acid under a Class-100 HEPA-filtered clean hood and left to digest for 60 days prior to analysis. Elemental concentrations were anlayzed by M. Handley using a Thermo Element XR Inductively Coupled Plasma Mass Spectrometer (ICP-MS) equipped with an ESI Apex 2 Q inlet system. Elements analyzed included: Ag, Al, As, B, Ba, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Fe, Gd, Ho, K, La, Li, Lu, Mg, Mn, Mo, Na, Nd, Ni, P, Pb, Pr, S, Sb, Sc, Si, Sm, Sr, Tb, Th, Ti, Tm, U, V, W, Y, Yb, Zn, and Zr.

Samples for ion chromatography were collected into polypropylene vials previously washed with deionized water. Major anions and cations (NO_3^-, SO_4^{2-}, Cl^-, Ca^{2+}, Na^+, Mg^{2+}, and K^+) were analyzed by E. Korotkikh using a Thermo Scientific™ Dionex™ ICS-6000 system with suppressed conductivity detection and a Dionex AS-HV autosampler.

Stable water isotope ratios (δD and $\delta^{18}O$) were measured by D. Introne from the outer melt fraction using a Picarro L-2130-i

Ring Down Spectrometer with a high-throughput vaporizer (Model A0212), following the method described by Introne (2024). Isotopic results are reported in per mil (‰) relative to the Vienna Standard Mean Ocean Water (VSMOW) reference (Reissig, 1983; Introne, 2024).

RESULTS

4.1 Water Isotopes and Lapse Rate

The SCG δD record is relatively smoothed (Figure 4), consistent with isotopic diffusion expected in old, compressed ice. Despite this smoothing, a distinct range in δD values is preserved, from approximately –125 to –240 ‰, reflecting considerable variability in source region, atmospheric conditions, and elevation. These values are comparable to the range found in Antarctic ice cores, spanning from coastal sites to elevations of 1000–1500 m asl (Hou et al., 2003).

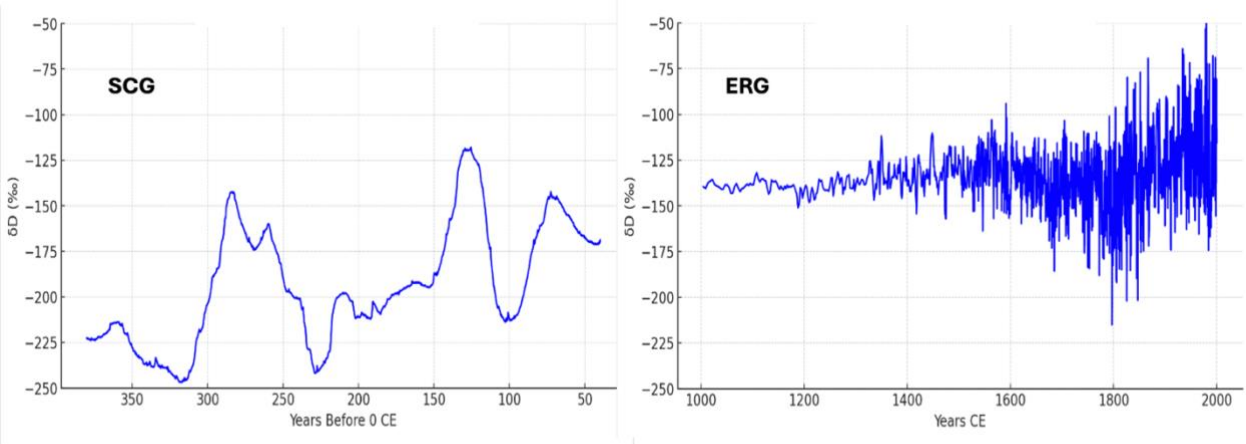

Figure 4. SCG δD (%) ~50 to ~350 Years Before 0 CE. ERG δD (%) 1000-2000 Years CE. Vertical scale the same on both plots.

Water isotopes in the Himalayas vary seasonally, with more negative values generally associated with winter precipitation and less negative values corresponding to summer monsoon conditions. They also show a strong negative correlation with elevation and a positive correlation with temperature. Yang et al. (2023) reported an average lapse rate of –2.48 ‰ per 100 m for δD across the Nepal Himalayas. The SCG δD mean value of –190 ± 31 ‰ was compared to the ERG δD mean of –137 ± 14 ‰, based on the period 1000–1800 CE to minimize potential anthropogenic effects. This comparison yields a lapse rate of approximately –3.53 ‰ per 100 m over the 1500 m elevation difference between SCG and ERG, slightly steeper than the lapse rate reported by Yang et al. (2023), but consistent with the extreme elevation range represented here.

This elevation-based comparison demonstrates the utility of the SCG isotope record for extending lapse rate estimates to higher altitudes than previously available. While the SCG core does not preserve a continuous record up to the present, the stable isotope values capture a multi-century snapshot of the atmospheric conditions that influenced precipitation on Mt. Everest during the latter half of the first millennium BCE.

4.2 Marine and Agriculture Source Southerly Air Masses

Primary sources of nitrate (NO_3^-) and ammonium (NH_4^+) in the SCG record are likely associated with agricultural activity and biomass burning across the Indo-Gangetic Plains (Mayewski et al., 1983, 1984). These emissions are seasonally transported toward the Himalayas during the summer monsoon, and the generally positive correlation between δD and both NO_3^- and NH_4^+ concentrations (Figure 5) is consistent with input from warmer, moisture-rich air masses originating to the south.

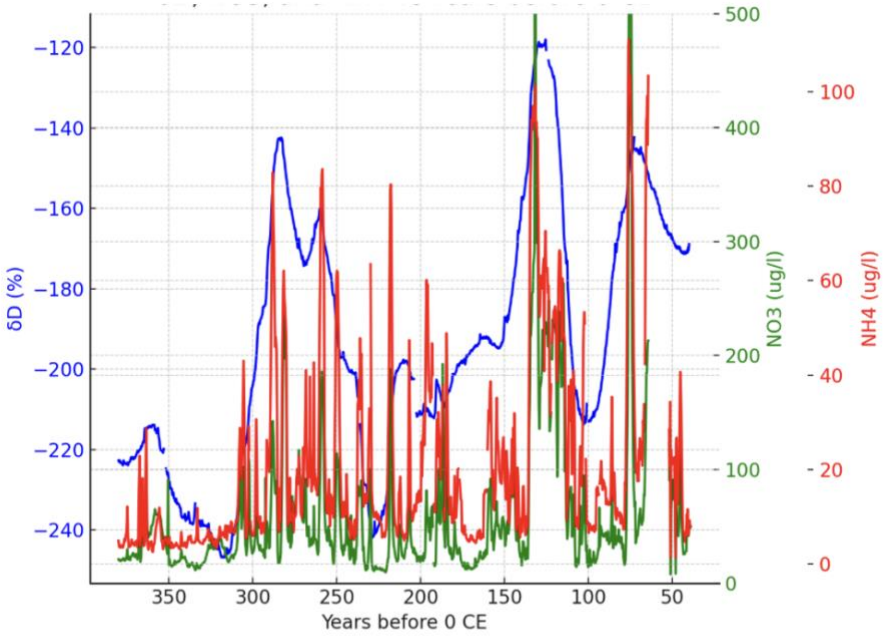

Figure 5. SCG δD (%), blue, NH_4 (red) and NO_3 (green) (both in ug/l) over the period the ~400 years before 0 CE.

Assuming a similar source region for nitrate, SCG NO_3^- concentrations (mean 139 ± 63 µg/L) are comparable to ERG values (mean 113 ± 96 µg/L), based on the period 1000–1800 CE, selected to reduce potential anthropogenic interference. The slightly higher SCG values may

reflect additional NO_3^- input from upper atmospheric sources, as SCG is located closer to the tropopause.

The relationship between δD and both sodium (Na^+) and chloride (Cl^-) (Figure 6) is positive, suggesting a marine aerosol contribution associated with southerly air mass incursions. SCG Na^+ and Cl^- concentrations are 30 ± 168 µg/L and 21 ± 70 µg/L, respectively. These values are broadly similar to those from ERG (Na^+: 19.7 ± 95 µg/L; Cl^-: 24.9 ± 132 µg/L), again using the 1000–1800 CE interval. The similarity in concentrations across an elevation difference of ~1500 m and a lateral distance of ~6.5 km indicates that marine-source soluble ions are not significantly depleted by elevation in this region.

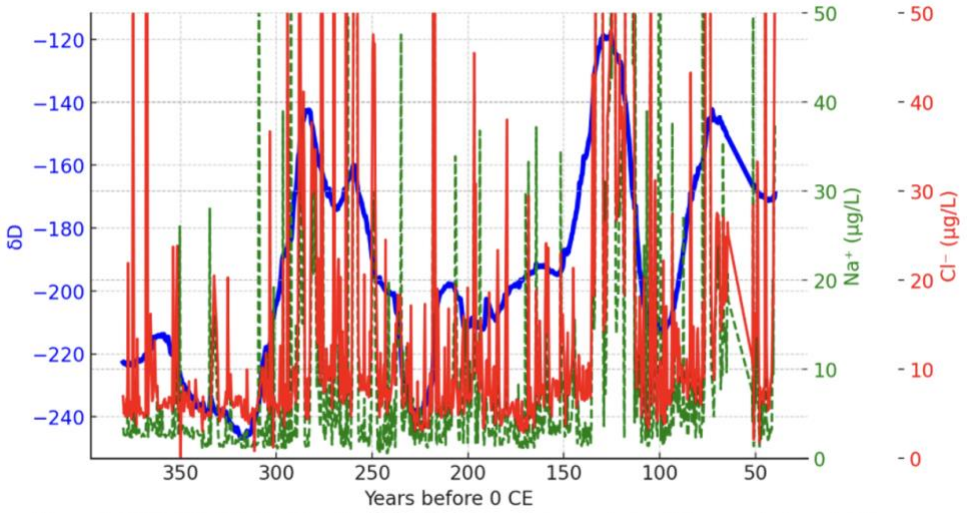

Figure 6. SCG δ D (%), Na^+ (ug/l) and Cl^- (ug/l) over the period ~400 years before 0 CE.

The Na^+/Cl^- ratio in seawater is 0.556 and the SCG and ERG ratios are 0.78 and 0.79, respectively, which suggests that in addition to marine aerosol input, there is a contribution from dust-bearing continental sources. These may include the arid regions of the Tibetan Plateau and surrounding snow-free terrain. The relatively higher mean Na^+ concentration at SCG may reflect its proximity to the Plateau, as well as its positioning at a more exposed, higher-altitude site where finer particles are more likely to be entrained and preserved.

The association between relatively less negative δD values and increased concentrations of NO_3^-, NH_4^+, Na^+, and Cl^- supports the interpretation that these species are primarily delivered to both SCG and ERG by southerly, summer monsoon-related circulation systems. These findings further confirm the influence of seasonality and regional atmospheric transport in shaping the chemistry of precipitation over Mt. Everest (Mayewski et al., 1983, 1984; Yang et al., 2023).

4.3 Dusts

SCG ice core concentrations of major, trace, and rare earth elements are generally lower than those observed in the East Rongbuk Glacier (ERG) ice core, where comparable data are available for elements such as Al, Ba, Ca, Ce, Co, Cr, Cs, Dy, Er, Eu, Fe, Gd, Ho, La, Lu, Mg, Mn, Nd, Pr, Sm, Sr, Tb, Ti, Tm, U, V, and Yb. In support of this a direct comparison of lanthanum (La) concentrations between SCG and ERG is shown in Figure 7. However, concentrations of Bi, K, and S are similar between the two sites, possibly suggesting more

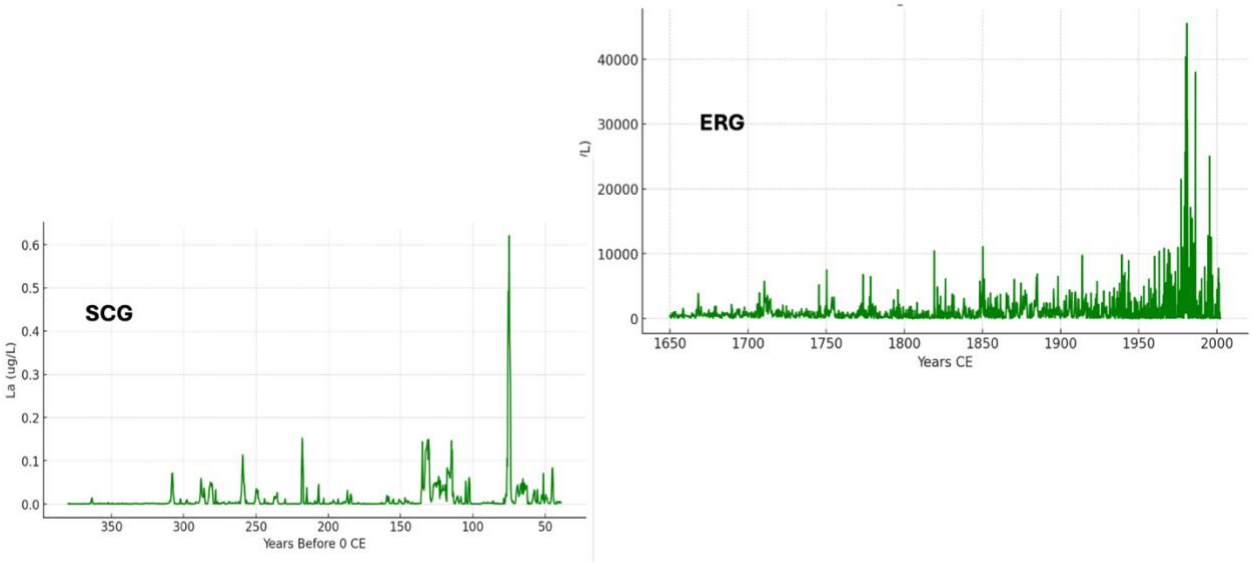

Figure 7. La (ug/l) ~50 to ~350 Years Before 0 CE. ERG La (ug/l)1650-2000 Years CE. Vertical scales differ.

proximal sources for these elements or greater efficiency in their long-range transport, perhaps due to finer grain size or differences in atmospheric residence time.

While the SCG and ERG records represent different time periods—SCG covering approximately 400 years before 0 CE and ERG spanning the last ~1000 years—source differences and air mass trajectories cannot be excluded as contributing factors. Nevertheless, the more likely explanation for the difference in overall elemental concentrations is the ~1500 m elevation difference between the two sites. SCG, being situated at a much higher elevation, likely receives lower concentrations of dust due to gravitational filtering and atmospheric scavenging during upward transport.

Closer examination of selected dust-related elements in the SCG record, specifically Fe, La, and U, reveals that higher concentrations of these elements are generally associated with less negative δD values (Figure 8). This pattern suggests increased dust input during relatively warmer periods, which may be linked to reduced snow cover, drier surface conditions, or enhanced wind activity in source regions such as the Tibetan Plateau to the north and Rajasthan, India to the south.

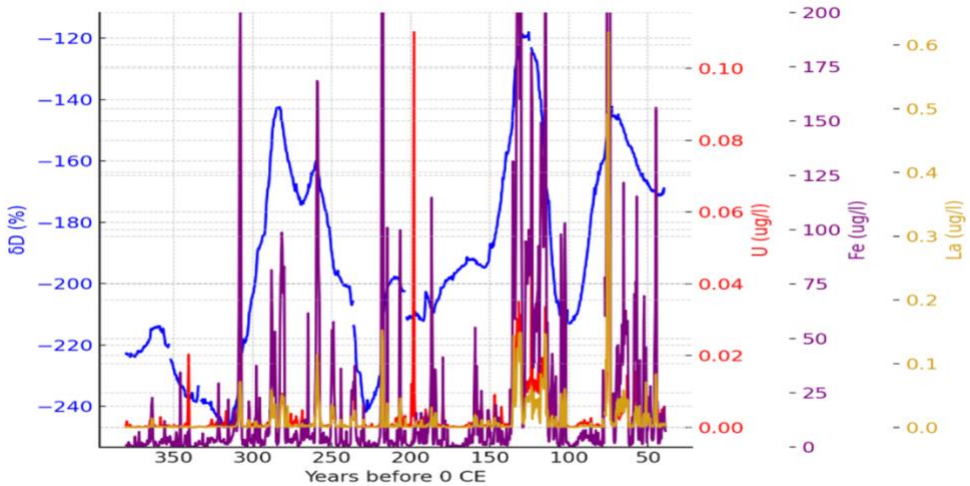

Figure 8. SCG δ D (%), U (ug/l) , Fe (ug/l) and La (ug/l) over the period ~400 years before 0 CE.

A particularly prominent increase in Fe, La, and U concentrations is observed around 115–135 years before 0 CE (Figure 9), coinciding with the least negative δD values in the SCG record. This ~20-year-long interval appears to represent a period of especially intense dust entrainment and transport. Based on apparent "annual layer" counting, the onset and termination of this event occurred within approximately 2–5 years, and the synchronous behavior of these three elements points to a coherent atmospheric signal. The event provides a clear example of the potential for highly resolved, compressed ice to preserve abrupt environmental changes even at this extreme elevation.

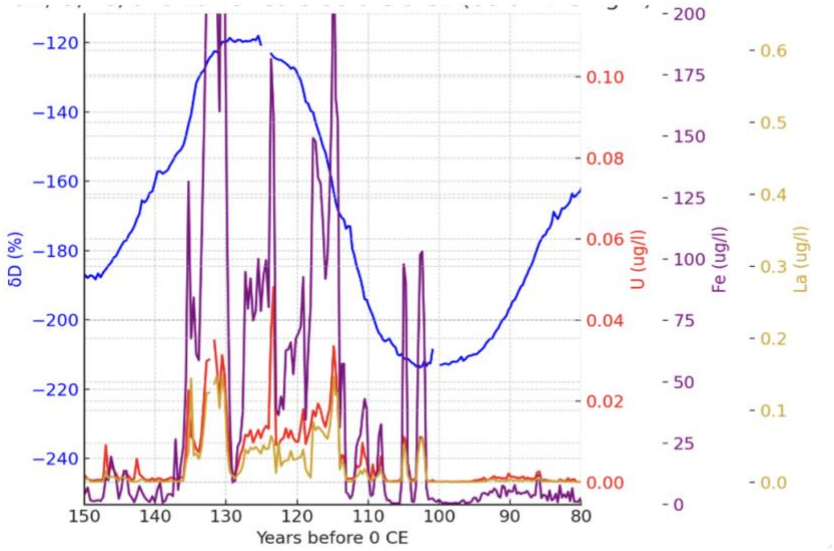

Figure 9. SCG δ D (%), U (ug/l) , Fe (ug/l) and La (ug/l) over the period ~80 to ~150 years before 0 CE.

4.4 Early Anthropogenic Activity

There is a prominent shift in the SCG ice core record in silver (Ag) and cobalt (Co) beginning around ~200–150 years before 0 CE (Figure 10). This trend, while subtle, may indicate the onset of anthropogenic emission influences in the region. The timing corresponds with known periods of early mining and metallurgical activity in several ancient civilizations.

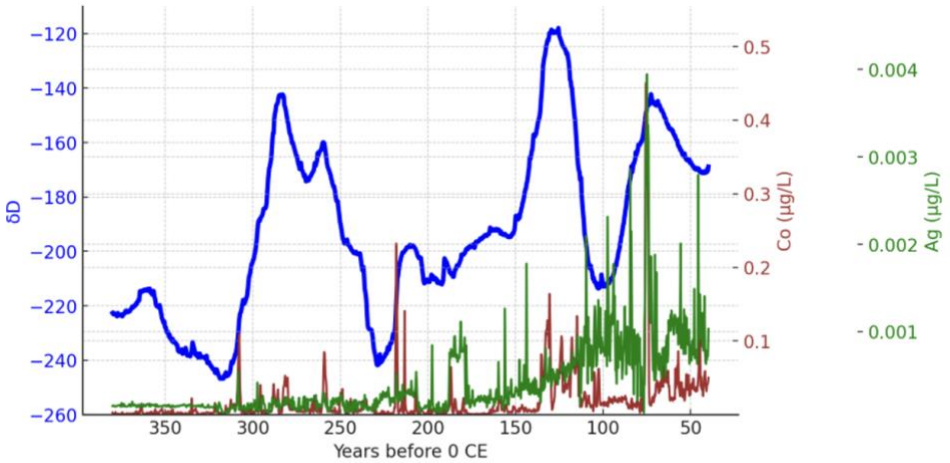

Figure 10. SCG δ D (%), Co (ug/l) and Ag (ug/l) over the period ~400 years before 0 CE.

The historical record suggests that Ag and Co extraction began to increase during the last several centuries before 0 CE, particularly across parts of the Indus and Roman worlds (Prasad, 1990). Mining and smelting of these metals were especially prominent in areas such as Rajasthan, India, a region well-positioned to serve as a potential dust and aerosol source for SCG via prevailing southerly circulation patterns (Craddock, 2014).

While the Ag and Co values in the SCG core remain below standard quantitative thresholds, the shift in their behavior near 200–150 years before 0 CE warrants further investigation. The coherence of these trends in relation to δD and dust-associated elements suggests a possible anthropogenic contribution superimposed on a broader environmental signal. This interpretation remains speculative, but highlights the potential of ultra-high-elevation ice cores to preserve early signatures of human activity in South Asia.

4.5 East Rongbuk Glacier Comparison Highlights

To place the SCG ice core record in broader context, we compare it with data from the East Rongbuk Glacier (ERG), located approximately 6.5 km to the north of SCG at a lower elevation (6518 m). The ERG ice core, recovered and analyzed by a joint US-Chinese team (Kang et al., 2000, 2001; Hou et al., 2003; Zhang et al., 2003; Kaspari et al., 2007, 2008, 2009a, 2009b, 2011), spans the last ~1000 years and provides a valuable reference for evaluating long-term changes in atmospheric chemistry and transport processes across the Everest region.

The SCG record differs notably from ERG in that it does not preserve recent layers; instead, it captures a snapshot of atmospheric conditions from approximately 2400 to 2000 years before present. Despite this difference in age, the SCG and ERG datasets reveal several important similarities and contrasts that provide insight into the processes governing atmospheric deposition at extreme elevations.

Water isotope comparisons between the two sites show a clear elevation-dependent lapse rate in δD, as discussed earlier, with SCG exhibiting more negative values overall. For major ions such as NO_3^-, NH_4^+, Na^+, and Cl^-, SCG concentrations are broadly similar to those observed in ERG, suggesting that regional atmospheric transport processes deliver these soluble species relatively efficiently to both elevations. The similarity in mean concentrations, particularly for NO_3^- and Cl^-, implies that scavenging loss with elevation may be limited, especially for marine and agricultural source aerosols during the summer monsoon (Mayewski et al., 1983, 1984).

In contrast, SCG concentrations for many dust-related elements (e.g., Al, Fe, La, U) are lower than those found in ERG. This is likely due to gravitational filtering and reduced particle loading at higher elevation, as finer and more easily transported particles are preferentially delivered to the SCG site. However, the similarity in concentrations for elements such as Bi, S, and K between SCG and ERG suggests that source proximity, grain size, or chemical reactivity may enhance their atmospheric residence and vertical transport.

While the SCG and ERG records reflect different time intervals, the comparison highlights the consistent influence of monsoonal air masses, the effects of elevation on aerosol composition, and the capacity of ultra-high elevation sites to preserve distinctive chemical signals. Together, the two records provide a complementary view of past atmospheric chemistry over the summit region of Mt. Everest.

DISCUSSION

The SCG ice core offers a unique opportunity to examine the chemistry of the atmosphere from the highest glacier on Earth. Although the core is not continuous and does not

capture the most recent ~2000 years, it preserves a well-resolved record from approximately 2400 to 2000 years before present. The SCG site, located just below the summit of Mt. Everest at 8020 m, lies near the tropopause in a region climbers refer to as the "Death Zone." Few environmental records exist from this elevation, and the glaciochemical data presented here reflect conditions near the interface between tropospheric and stratospheric processes.

Despite its short length, the SCG core reveals several compelling patterns in atmospheric chemistry and climate. First, the water isotope signal is smoothed but preserves a broad range of δD values (~–125 to –240 ‰), consistent with diffusive processes expected in dense, ancient ice. The isotopic lapse rate between SCG and the lower ERG site (~3.53 ‰/100 m) is slightly steeper than previous estimates (Yang et al., 2023), possibly reflecting the extreme elevation contrast and reduced atmospheric pressure at SCG. These results contribute to a better understanding of isotope-elevation relationships in the upper troposphere over the Himalaya.

Second, the co-variation of δD with NO_3^-, NH_4^+, Na^+, and Cl^- supports the hypothesis that southerly, summer monsoon-related air masses are the dominant source for these species. This agrees with earlier studies documenting Indo-Gangetic Plain agricultural and marine aerosol contributions to high-elevation Himalayan snowfall (Mayewski et al., 1983, 1984). The similarity in ion concentrations between SCG and ERG, despite the elevation difference, suggests that soluble aerosol transport to Everest is not significantly diminished with altitude for these compounds.

Third, trace and rare earth element concentrations are generally lower at SCG than at ERG, particularly for dust-associated species such as Fe, La, and U. This is likely due to enhanced gravitational filtering and reduced atmospheric loading at higher elevations. However, elements like Bi, S, and K display similar concentrations in both cores, possibly due to their smaller particle size, enhanced residence time, or more efficient transport mechanisms. Notably, the strong co-occurrence of Fe, La, and U during a ~20-year-long warm phase (~115–135 years before 0 CE) suggests an episode of intense dust entrainment and delivery from source regions such as the Tibetan Plateau and Rajasthan (Kaspari et al., 2009b; Potocki et al., 2022). The abrupt onset and decay of this event over 2–5 years, as determined through annual layer counting, demonstrates that highly compressed ice at SCG can preserve signatures of short-term environmental variability.

Fourth, the SCG record shows a detectable trend in Ag and Co beginning around 200–150 years before 0 CE. Although these values fall below standard ICP-MS detection limits, the consistent directional change suggests possible early anthropogenic influence. This timing aligns with known periods of silver and cobalt mining in regions of South Asia such as Rajasthan (Prasad, 1990; Craddock, 2014). The possibility that high-elevation ice in the Himalaya preserves signals of early metallurgical activity provides a valuable incentive for further investigation.

These findings build on earlier work from the same expedition (Potocki et al., 2022), which demonstrated that recent warming has caused widespread loss of snow and firn at SCG, resulting in ice surface exposure and net thinning exceeding 2 meters of water equivalent per year. Modeling and radiocarbon dating from that study indicate that ~55 meters of ice have been lost over the past few decades. The present study complements that work by showing that even in this thinned state, the remaining ice contains meaningful climatic and geochemical signals.

Figure 9 underscores the importance of high-resolution sampling for detecting abrupt changes. Our discrete sampling (1.04 cm resolution) provides only ~2–3 samples per year over the ~400-year span of the SCG record. While this is marginal for annual layer resolution,

comparison with ultra-high-resolution LA-ICP-MS analysis (~120 micron resolution) that we have undertaken for other ice cores confirms that annual and seasonal signals can be recovered (eg., Sneed et al., 2015; Spaulding et al., 2017). Future work would benefit from applying this method across a greater portion of the SCG core to assess the persistence of short-lived events and refine temporal resolution.

Although interpretation of the SCG record is limited by the lack of a surface-to-bottom chronology, its location, elevation, and preservation of ancient atmospheric chemistry make it a critical archive—one that may soon be lost. The disappearance of SCG will eliminate the possibility of future sampling from this unique atmospheric regime. As such, these data serve not only as a scientific resource but also as a call to action in documenting and understanding high-elevation cryospheric change before it disappears.

CONCLUSION

The SCG ice core provides the first geochemical and isotopic record of the atmosphere from the highest glacier on Earth. Although the upper ~2000 years of accumulation have been lost due to recent ice thinning, the preserved ~400-year record from the latter half of the first millennium BCE offers new insights into the atmospheric conditions over Mt. Everest during this period. Isotope-derived lapse rates, elemental comparisons, and dust proxies reveal the influence of seasonal monsoon transport, elevation-driven filtering, and potentially early anthropogenic activity.

Comparison with the lower elevation ERG core demonstrates that despite SCG's extreme altitude, soluble ions from marine and agricultural sources are efficiently transported to this region, while dust-associated elements are more effectively filtered with elevation. A distinct multi-decadal dust event, preserved even in compressed SCG ice, highlights the potential for capturing short-term climate variability at ultra-high elevation when sampling resolution is sufficient.

While the interpretation of SCG is limited by its discontinuous nature and lack of modern accumulation, its scientific value is underscored by the fact that this record will likely not be recoverable again. Ongoing and future ice loss in the region is expected to eliminate this archive entirely within decades. The SCG ice core serves as a critical snapshot of the pre-industrial atmosphere from a location close to the top of the Earth, and its preservation underscores the urgency of documenting disappearing high-elevation glacial systems before they are lost.

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Acknowledgements:

The South Col Glacier research was conducted through a partnership with National Geographic Society, Rolex, and Tribhuvan University, with approval from all relevant agencies of the Government of Nepal. We thank the communities of the Khumbu Region, Xtreme Climbers Treks and Expedition P. Ltd, Jiban Ghimire, and Shangri-La Nepal Trek Pvt. Ltd. The high-altitude Sherpa team included: Panuru Sherpa (Sirdar), Phu Tashi Sherpa, Pemba Sherpa, Urken Lendu Sherpa, Ila Nuru Sherpa, Fura Chetten Sherpa, Lakpa Gyaljen Sherpa, Pasang Sona Sherpa, Pasang Kami Sherpa, Nima Rita Sherpa, Tenzing Gyanjen Sherpa, Nawang Phinjo Sherpa, Phinjo Sherpa, and Gyaljen Dorji Sherpa. Dawa Yangzum Sherpa, Amrit Ale, Mark Fisher, Dirk Collins, and Eric Daft are also thanked for helping to ensure a successful and safe climb conducted with good humor. Many thanks to Sandra Elvin, Pete Athans, Freddie Wilkinson, Aurora Elmore, Tyler Dinley, and many others of the National Geographic logistics and storytelling staff, the United States Embassy in Kathmandu, Fisher Creative, our fellow team members and all of the porters, people, and businesses in the Khumbu Valley. Radiocarbon analysis was conducted by Ling Fang and Margit Schwikowski from Paul Scherrer Institute at the Laboratory for the Analysis of Radiocarbon with the University of Bern AMS, Switzerland. This paper is dedicated to Urken Lendu Sherpa, a member of our Summit team, who died climbing in 2021.

The East Rongbuk research was funded by NSF ATM 0139491 (Mayewski), NOAA NA05OAR4311109 (Mayewski), the Natural Science Foundation of China (90411003 and 40401054), and the Chinese Academy of Sciences (''Talents Project'' and the 3rd Innovation Programs: KZCX3-SW-339.

All stable isotope, major ions and major/trcae/rare earth elent analyses were conducted by D. Introne, E. Korotkikh and M. handley, respectively.

All plots were made using ChatGPT.

Data and availability:

All data can be accessed via https://www.icecoredata.org/Others.html#