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Ice-core records of human impacts on the environment

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Ice cores can provide high-resolution records of anthropogenic activities, observable in gas and impurity records, for at least the last few millennia. Such archives demonstrate the ubiquity of human influence and the importance of legislation in mitigating these impacts.

Ice cores archive direct and proxy records of human impacts on the environment. The impact of human activity on the environment is clearly visible in ice cores as: increasing concentrations of methane and other greenhouse gases (e.g. Banerjee et al. p. 104; Mitchell et al. 2013); spikes in radionuclides from atomic bomb explosions (e.g. Gabrielli and Vallelonga 2015); and elevated concentrations of pollutants like lead, microplastics, and black carbon (e.g. Materić et al. 2022; Gabrielli and Vallelonga 2015; Fig. 1).

Ice-core records also extend much further into the past than modern observations, revealing the widespread extent of historical anthropogenic impacts. Here, we focus on methane and lead, two chemical species that record some of the earliest ice-core evidence of human impacts on the environment, beginning at least 2500 years ago. Additionally, we discuss examples of ice-core records that show the impact of remediation actions including legislation and technological advancements in reducing anthropogenic influence.

Methane emissions from early agriculture

Ice cores record changes in the composition of the atmosphere in air bubbles that get trapped as snow and ice accumulate. Air bubbles in ice cores from both Greenland and Antarctica record a steady 100-ppb increase in atmospheric methane concentrations beginning around 5000 years ago. There has been much debate about whether this reflects natural variability or is evidence of early human influence on the environment via land clearance and agriculture, such as rice and livestock farming. Fortunately, ice cores offer tools to investigate this question. For example, the difference in methane concentration between Arctic and Antarctic ice cores tells us which hemisphere has larger emissions. Additionally, the isotopic composition of methane in the ice preserves a fingerprint of where and how it was produced. Using these techniques, ice cores reveal that the increase between 5000 and 2000 years ago likely came from stronger monsoons in the Southern Hemisphere, rather than rice farming in East Asia (Beck et al. 2018). Studying these natural variations allows us to better identify the impact of human activity.

Anthropogenic methane emissions became truly significant during the last 2000 years (Fig. 1). During this period, the rise in methane concentrations in the ice cores cannot be explained without the increase of emissions from human activity, such as rice and cattle farming and decomposition in landfills (Mitchell et al. 2013). The sensitivity of methane emissions to human population and industry is also evident in the sharp dips in Northern Hemisphere emissions coinciding with the fall of the Roman Empire and Han Dynasty (Sapart et al. 2012), the arrival of the Black Plague in Asia (Mitchell et al. 2013), and the deaths of Indigenous Americans resulting from European invasion and subsequent disease introduction (Ferretti et al. 2005).

Human impacts on lead pollution

Anthropogenic emissions of lead, a toxic heavy metal emitted from industrial activities including mining and fossil-fuel burning, are first observed in Arctic ice cores approximately 3000 years ago (e.g. Murozumi et al. 1969), with earliest evidence of lead pollution attributed to the expansion of the Phoenician society (McConnell et al. 2018). Antarctic ice cores record anthropogenic lead pollution only during the last 130 years due to lower emissions in the Southern Hemisphere, with earliest emissions from mining and smelting of lead ores in Australia (Vallelonga et al. 2002). High-resolution ice-core records demonstrate the sensitivity of ice cores to year-to-year and decade-to-decade changes in anthropogenic emissions corresponding to major historical events including plagues, wars, and periods of economic stability (e.g. McConnell et al. 2018).

Arctic lead pollution rose rapidly during the industrial period, peaking in the 1960s, when leaded gasoline use was most prevalent. Indeed, Greenland ice cores indicate that

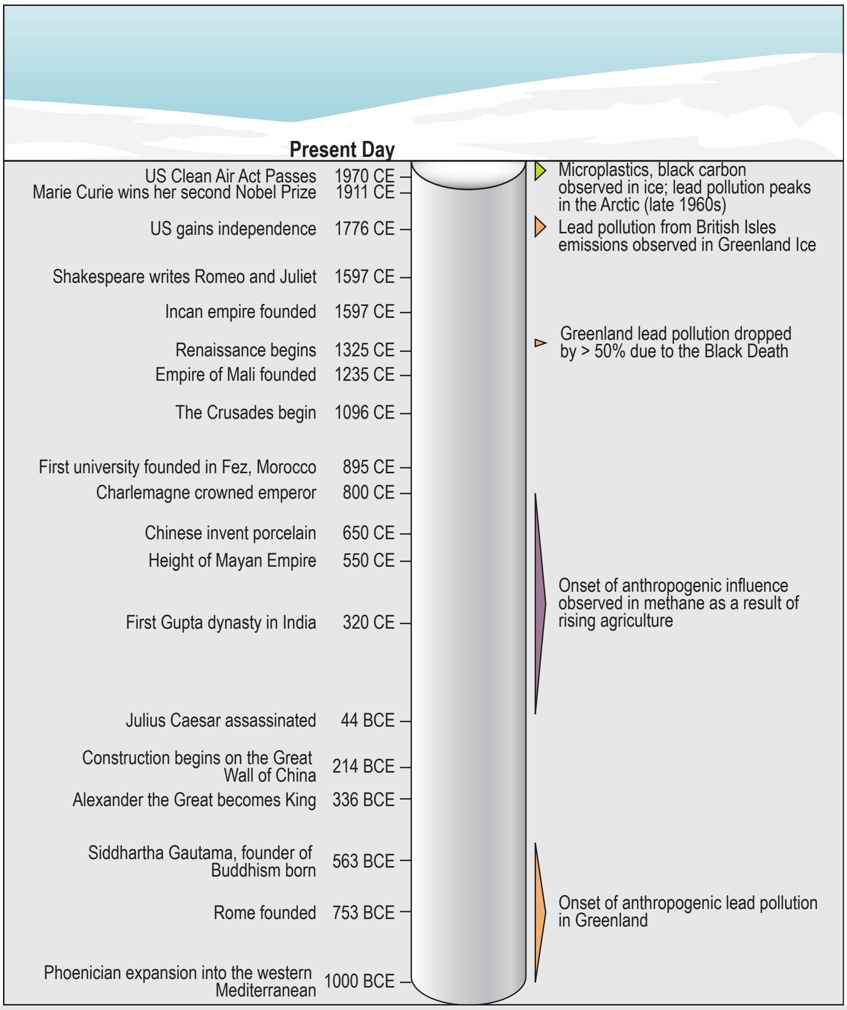

Figure 1: Schematic of an ice core, with present day representing the surface of an ice sheet or glacier, relevant historical markers on the left, and, on the right, a timeline of human activity archived in ice cores including anthropogenic methane (Mitchell et al. 2013; Beck et al. 2018), lead (Wensman et al. 2022; McConnell et al. 2018; 2019), microplastics (Materic et al. 2022) and black carbon (Gabrielli and Vallelonga 2015 and references therein). Triangles represent the timeframe of each event.

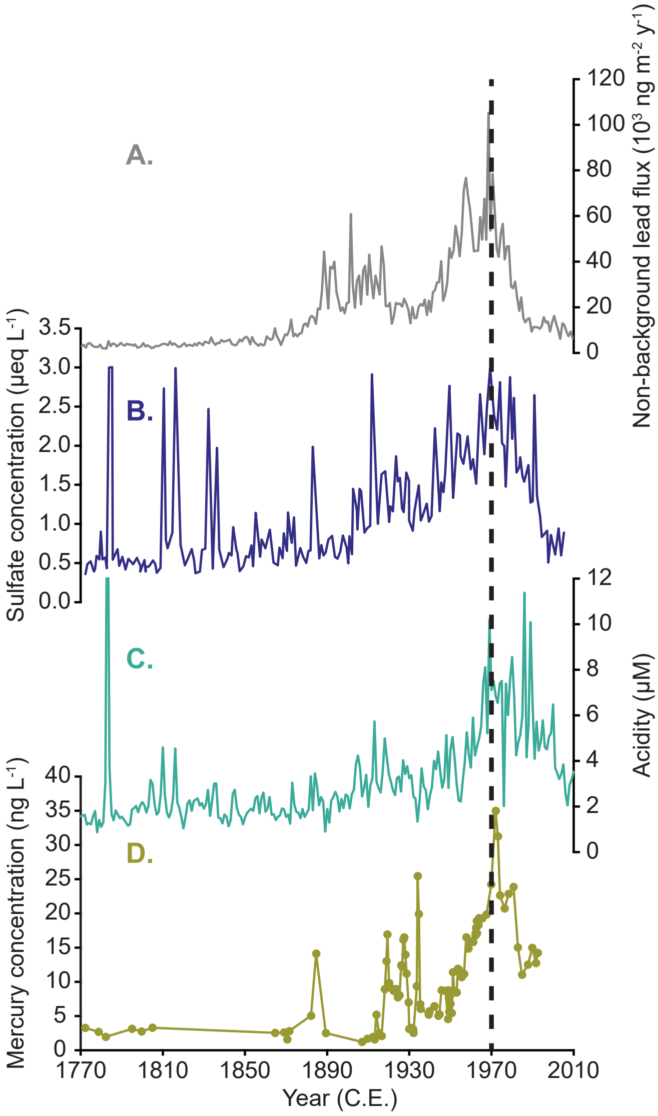

Figure 2: Ice-core records of environmental pollutants before and after enactment of the US Clean Air Act in 1970 (dashed line). **(A)** Lead flux from southern Greenland ice cores (McConnell et al. 2019); **(B)** Summit, Greenland, sulfate concentrations (Geng et al. 2014); **(C)** Acidity levels from northern Greenland (Maselli et al. 2017); and **(D)** Mercury concentrations from Upper Fremont Glacier in Wyoming, USA (Chellman et al. 2017).

Arctic lead pollution increased 250- to 300-fold between the Early Middle Ages and the 1960s (McConnell et al. 2019), with lead isotopic records suggesting predominantly US-derived sources (e.g. Wensman et al. 2022). Clair Patterson and colleagues first noted large-scale increases in lead pollution in Greenland ice associated with leaded gasoline use (e.g. Murozumi et al. 1969). Using ice cores to determine pre-industrial levels of lead pollution, they demonstrated that increased lead deposition was caused by anthropogenic emissions; these results influenced the passage of the US Clean Air Act in 1970.

Impact of environmental legislation

Following enactment of legislation in North America and Europe in the 1970s and 80s, ice cores show lead pollution declined rapidly, with current levels approximately 80% lower than during the height of leaded gasoline use, though deposition remains 60-fold higher than pre-industrial levels (McConnell et al. 2019; Fig. 2a). In addition to decreases in lead pollution, other pollutants also record evidence of positive human impacts following the US Clean Air Act, and similar legislation enacted around the world (e.g. Environment Action Programme in Europe). One example is the concentration of sulfates in ice from Summit Station in central Greenland. Sulfates primarily originate from coal burning, and therefore their atmospheric concentration increased after the Industrial Revolution. This increase was recorded in the Greenland Ice Sheet (Geng et al. 2014) until the enactment of the Clean Air Act, following which ice-core sulfate concentrations returned to pre-industrial levels (Fig. 2b). Measurements in ice cores also show decreased acidity levels following the Clean Air Act and ensuing market-based cap-and-trade systems (which set limits on allowable pollutant emissions for companies) for sulfur dioxide and nitrogen oxides, which are key chemical species in the formation of acid rain, produced as a byproduct of fossil-fuel burning (Fig. 2c; Maselli et al. 2017; Geng et al. 2014). At Upper Fremont Glacier in Wyoming, USA, there has been a sharp decrease in mercury levels (a toxic heavy metal and anthropogenic pollutant) recorded in the ice since the 1970s, due to the lack of recent volcanic activity and legislation requiring the addition of pollutant scrubbers to industrial flue-gas stacks (Fig. 2d; Chellman et al. 2017).

Ice-core records of pollutants demonstrate the importance of legislation regulating anthropogenic emissions and suggest further environmental legislation may result in continued reductions in anthropogenic emissions. As far as we are aware, no ice-core studies to date have incorporated Indigenous knowledge in interpretation of ice-core data; however, Indigenous experts can enhance our understanding of the role humans have played in shaping the environment and improve effectiveness of legislation. Previous examples of studies within the Earth sciences provide mechanisms for working across knowledge systems to create respectful, inclusive, and effective collaborations with Indigenous experts (e.g. Hill et al. 2020), including tracking sea-ice extent and thickness (Tremblay et al. 2008). Such collaborations could be impactful in ice-core science in, for example, expanding understanding of early pollution histories or impacts of long-range pollution transport, as observed in ice cores, on Indigenous Arctic populations.

Conclusion

The exponential acceleration and vast extent of anthropogenic disruption of the environment is uniquely recorded by a vast array of ice-core datasets. The historical context ice cores provide, by extending contemporary measurements into the past, will continue to be invaluable as previously undiscovered impacts emerge. Ice cores provide unique long-term records, highlighting both the level to which humans have altered remote environments, and the role legislation can have in reducing human influence.

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