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M. J. Pankhurst, C. J. Stevenson & B. C. Coldwell

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Authors (ORCID)

*M. J. Pankhurst[1,2] : 0000-0001-6844-9822

C. J. Stevenson[3] : 0000-0003-0406-9892

B. C. Coldwell[1,2] : 0000-0001-9240-6240

Affiliations

[1]Instituto Tecnológico y de Energías Renovables (ITER), 38600 Granadilla de Abona, Santa Cruz de Tenerife, Spain

[2]Instituto Volcanológico de Canarias (INVOLCAN), 38600 Granadilla de Abona, Santa Cruz de Tenerife, Spain

[3]Earth, Ocean and Ecological Sciences, University of Liverpool, Liverpool, L69 7ZX, UK

*Correspondence mpankhurst@iter.es

Abstract

Meteorite impacts load the atmosphere with dust and cover the Earth's surface with debris. They have long been debated as a trigger of mass extinctions through Earth's history. Impact winters generally last $<10^0$ years, whereas ejecta blankets persist for 10^3-10^5 years. Here we show that only meteorite impacts that emplaced ejecta blankets rich in K-feldspar (Kfs) correlate to Earth system crises (n=11, p<0.000005). Kfs is a powerful ice-nucleating aerosol yet is normally rare in atmospheric dust mineralogy. Ice nucleation plays an important role in cloud microphysics, which modulates global albedo. A conceptual model is proposed whereby the anomalous prevalence of Kfs is posited to have two key effects on cloud dynamics: 1) reducing the average albedo of mixed-phase cloud, which effected a hotter climate; 2) weakening of the cloud albedo feedback, which increased climate sensitivity. These mechanisms offer an explanation as to why this otherwise benign mineral is correlated so strongly with mass extinction events: every K-feldspar-rich ejecta blanket corresponds to a severe extinction episode over the past 600 Myr. This model may also explain why many kill mechanisms only variably correlate with extinction events through geological time: they coincide with these rare periods of climate destabilization by atmospheric Kfs.

Meteorite impact as a cause of 'mass' extinction has been vigorously debated since 1980 (Alvarez *et al.* 1980). The only two instances that have gained acceptance as mass extinction triggers are also the two largest in the past 600 Myr: Chicxulub with a transient crater diameter of ~85 km at the K-Pg boundary c. 66 Ma (Hull *et al.* 2020), and Acraman with a ~51 km-wide transient crater, associated with the Acritarch Crisis c. 580 Ma (Grey *et al.* 2003), see Fig. 1. This creates the impression that if any specific meteorite impact is to affect change at the global scale, extreme size is prerequisite (Tohver *et al.* 2012).

The primary kill mechanism invoked for a meteorite impact is Impact Winter. This is a short term phenomenon (Toon et al., 1997) whereby impact ejecta block out solar radiation, which directly affects photosynthetic life and global temperature. Hence, the larger the impact, the more severe these affects will be on the biosphere. This hypothesis implies very close temporal correlation between cause and effect that is predicated first upon size: larger meteorite impacts should affect the global biosphere in a geological instant, whereas smaller ones are predicted to not affect the biosphere at a global scale.

Age dating methods now provide high temporal resolution of impacts (Schmieder and Kring, 2019), as good or better than that of geological substages (see Supplementary Material). This shows that many smaller impacts (with a transient crater 10-20 km wide) occur in the same geological substage as severe ecological turnover (Fig. 1). However, many others correspond precisely with times of relatively stable or decreased global extinction rate (Rohde and Muller, 2005), including the fourth largest: Manicouagan, which had a transient impact crater ~48 km wide at 215.56 ±0.05 Ma.

Patterns of extinction temporally associated with meteorite impacts display a range of styles from catastrophic, to stepwise and graded (Kauffinan, 1994). Ecosystem recoveries and speciation largely took place in tandem on timescales up to a million years (Holland, 2020). Therefore, any argument for a causative link between meteorite impacts and mass extinctions must address (i) why many large impacts do not coincide with extinction events, (ii) why many smaller impacts do coincide with extinction events (Fig. 2), and also (iii) why the style, magnitude and timescales of potential kill mechanisms could be so different between instances.

Atmospheric ice nucleation efficiency

Recent advances in atmospheric science show that the mineralogy of aerosol is an important factor in climate function and sensitivity. K-feldspar (Kfs) is the most important mineral due to its role in nucleating ice in mixed-phase cloud (Atkinson *et al.* 2013; Vergara-Temprado *et al.* 2017). The degree of cloud glaciation modulates its albedo, and hence clouds' fundamental contribution to balancing the global radiation budget (Murray et al., 2020; Vergara-Temprado et al., 2018).

Meteorite impacts have the unique potential to produce sudden, major and persistent changes to atmospheric aerosol mineralogy (Coldwell and Pankhurst, 2019). By excavating local rocks and spreading them across the Earth's surface, the mineralogy of atmospheric dust is dominated by the composition of the rocks hit. The initial dust and debris cloud settles out of the atmosphere quickly (Toon et al., 1997), yet the ejecta blanket persists as a voluminous and readily aerosolised source of mineral dust to the lower atmosphere for tens to hundreds of thousands of years (White *et al.* 2001; Coldwell and Pankhurst 2019).

Here, we present an analysis of meteorite impacts and extinction rates over the past 600 Myr. A new parameter is incorporated into the analysis: the Kfs content across the Earth's surface after meteorite impacts. High Kfs content is a consistent feature of impacts coinciding with a mass extinction event. Time series statistical analysis of this correlation returns a *p* value of <0.000005, strongly indicating causation. In direct contrast, ejecta blankets low in Kfs are consistently associated with periods of ecological stability. We propose a conceptual model which posits Kfs as the driving agent behind these severe extinction events. It is the ejecta blanket's potential to change long-term climate, not Impact Winter, that determines the link between meteorite impact and mass extinction through deep time.

Meteorite Impacts and atmospheric mineralogy through deep time

Meteorite impact ejecta that blanket the Earth's surface have the unique potential to interrupt the clay-dominated atmospheric mineral aerosol regime at a global scale (Coldwell and Pankhurst, 2019). Among other effects, each impact resulted in the geologically instant production of fresh mineral dust in the readily aerosolised ≤200 μm diameter fraction that was likely ~10-1000 × that of total modern annual dust emissions (Coldwell and Pankhurst, 2019). How persistent an interruption is depends upon the initial subaerial area affected, how the ejecta blanket is mechanically broken down making more fresh minerals available for aerosolization, and the speed and pervasiveness of chemical

weathering which acts to restore the clay barrier (Coldwell and Pankhurst, 2019). Based on laboratory and field studies, reasonable estimates for complete Kfs chemical breakdown inside a highly porous blanket range to over a million years (White et al., 2001). The rate of ejecta blanket removal will decelerate through time owing to its thinner average depth with distance from the crater, hence its period of influence on atmospheric mineralogy is likely to be on the order of tens to hundreds of thousands of years (Coldwell and Pankhurst, 2019).

The Earths' crust is a heterogeneous arrangement of rock types, and meteorite impact location is serendipitous. The Kfs content of target rocks of all recorded meteorite impacts in the last 600 Myr with transient crater diameter ≥10 km were recently reviewed (Coldwell and Pankhurst, 2019). Post-impact average Earth surface KFF (% by volume of Kfs in a material: Pankhurst 2017) was estimated as part of that review by using palaeogeographic reconstructions of the continents, and primary ejecta dispersal. These KFF estimates allow comparison between different meteorite impacts and their potential effects on the Earth system through time.

Calculations

Compared to Coldwell and Pankhurst (2019), this study adds estimations of global surface average KFF for the Clearwater West and Saint Martin impacts; uses refined ages for the Carswell, Charlevoix, Dellen, Puchezh-Katunki and Steen River impacts; and discards the Woodleigh impact on age-precision arguments (Schmieder and Kring 2019), for a total of 33 impacts. Fifteen ejecta blankets resulted in increased global Kfs availability, the other 18 did not (Supp. Fig. 1b, see also Coldwell and Pankhurst 2019).

The timing of these ejecta blankets is compared to the timing of extinction events over the past 600 Myr. It is important to consider the nature of the extinction record in this comparison, since statistical artefacts and record completeness produce bias at different times and timescales (Foote 2003; Bambach 2006; Holland 2020). A number of data treatments and tabulation methods are available in order to identify candidate extinction events (Foote 2003; Bambach 2006; Kocsis *et al.* 2019; Holland 2020; The Paleobiology Database 2021).

In this case, the most robust approach is to use a record that has the highest temporal resolution possible, whilst applying consistent data treatment. The marine fossil record is the longest and best-preserved, and at the highest temporal resolution available for inter-comparison at the genera level (Rohde and Muller 2005) contains 167 biostratigraphic sub-stages from ca. 565 Ma to present (Fig. 1b). A review of extinction studies that focused on the marine record, and representing a range of data treatments and temporal resolutions, identifies 18 intervals as those that most consistently appear as candidate mass extinction episodes over deep time (Bambach 2006) using Sepkoski's original definition (Sepkoski 1986). Five additional extinction events are recognised when applying a complementary treatment (Rohde and Muller 2005), for a total of 23 extinction events for inclusion. Each extinction event is also identifiable at lower temporal resolution (see the Palaeontology Database 2021). However, it is the high-resolution and consistent approach that provide the most robust method of recognising or rejecting a correlation with the independent meteorite impact database.

Radiometric ages of large meteorite impacts are now mostly derived from dating authigenic minerals or glass from impact melts (Schmieder and Kring 2019). These impact age data are more precise than the duration of sub-stages (see Supp.). Using the span of time defined by the 2σ age precision of each impact, 13 are resolved to a single substage (see Fig. 2), which allows for direct comparisons to be made at the 95% confidence level using the highest stratigraphic resolution (167 intervals), and a further 12 to one of two neighbouring sub-stages. To derive the statistical significance of potential correlations, the 167 geological stages/sub-stages were made into three binary sequences; whether or not they contain a severe extinction event; whether or not a meteorite impact occurred; and whether or not an ejecta blanket resulting from an impact caused an increase in Kfs across the Earth's surface. Event analysis using the *R* package *CoinCalc* (Siegmund *et al.* 2017) was conducted for a range of subsets defined by age-dating precision (Supp.).

Results

Three key observations are made by comparing the high-resolution meteorite impact and marine fossil records (Figs 1 and 2). First, every meteorite impact whose ejecta blanket was rich in Kfs coincides with, or tightly overlaps (within impact age precision), a sub-stage containing a severe extinction episode. Second, none of the impacts deficient in Kfs coincide with an extinction event, with

the exception of one that overlaps within (comparatively poor) age precision. Third, there is a poor correlation between impact size and extinction intensity (Fig. 2, see SFig. 3A for alternative projections). In addition, we note that each of the marine extinctions corresponding to a Kfs-rich ejecta blanket also have an associated terrestrial extinction (Bond and Grasby 2017).

Time series event analysis demonstrates that extinction episodes correlate strongly with the Kfs-rich ejecta blankets. The most conservative statistical approach using the entire database but counting only *exact* simultaneity as true positives returns a *p* value <0.000005. Conversely, the null hypothesis is accepted when applying the same method to Kfs-poor ejecta blankets, and all meteorite impacts taken together, i.e. there is no correlation between Kfs-poor impacts or meteorite impacts in general, and severe extinction episodes (Fig. 3, Supp.).

The KFF parameter cleanly discriminates between those meteorite impacts that coincide with severe extinction episodes, and those that do not. The strength of the temporal correlation between Kfs-rich ejecta blankets and severe extinction episodes suggests a causal link. The clear anti-correlation between Kfs-deficient ejecta blankets and extinction intensity suggests that meteorite impacts themselves are not causally related to severe extinction events. Such is the number of true positives compared to the dataset sizes that adjustments to what constitutes an extinction "event", either qualitatively (i.e. by taxa/community) or quantitatively (i.e. by thresholding to an extinction intensity rate) do not change the result that Kfs ejecta blankets, not meteorite impacts, are strongly associated with severe extinction episodes.

Discussion

Kfs has been a major constituent of the Earth's upper crust for >2 billion years, is present and often common in most soil types (Pankhurst 2017), and is not considered adverse to life (Mohammed *et al.* 2014). Kfs does not readily convert into secondary chemical compounds while in the atmosphere. This benign chemical nature contrasts sharply with other materials discussed in the literature that are excavated and/or formed as a result of meteorite impacts, including sulphurous aerosol and hydrocarbons that cause acid rain, ozone depletion and increased atmospheric CO_2 (Kaiho *et al.* 2001; Ohno *et al.* 2014; Kaiho and Oshima 2017).

Whilst not chemically gregarious, Kfs has been shown to be the most powerful ice-nucleating mineral in the modern atmosphere (e.g. Harrison *et al.* 2019). As such, we draw upon our understanding of the modern climate system and cloud physics to explore how ejecta blanket mineralogy could affect the Earth's paleoclimate. From this we propose a conceptual model whereby Kfs-rich ejecta blankets can profoundly influence cloud dynamics, their albedo, and in turn global climate.

Clouds and Earth's radiative balance

Cloud plays a fundamental role in maintaining balance of the global energy budget since clouds are both reflectors of radiation from space, and insulators of radiation from the Earth's surface (Boucher et al., 2013). The net contribution of cloud to defining Earth's 'thermostat' is determined by their coverage, temperature, and optical properties (Murray et al., 2020). Warm clouds form at low altitudes and are mainly composed of microscopic water droplets (Murray et al., 2020). Their dense arrangement produces an optical thickness that efficiently reflects solar radiation (high albedo). Warm clouds cover a significant proportion of the Earth's surface, which effects an important net cooling forcer on the climate (Boucher et al., 2013; Murray et al., 2020). In contrast, cold clouds occur at high altitude and are composed of ice crystals at low concentrations, which means they are optically thinner than warm clouds (Storelvmo *et al.* 2015; lower albedo: Murray *et al.* 2020). In addition, cold clouds are effective at absorbing infrared radiation emitted from the Earth's surface, which overall amounts to a small net warming effect (Boucher et al., 2013).

The presence of ice-nucleating particles (INPs) in the atmosphere modulates cloud properties between these end-members (Murray et al., 2020). Supercooled water freezes homogeneously at ~-35°C yet if INPs are present ice-nucleation is induced, sometimes at far warmer temperatures depending upon the efficiency of the INPs (Murray *et al.* 2012). This means water droplets at higher temperatures can convert to ice particles, and leads to production of mixed-phase cloud (Boucher et al., 2013). Higher proportions of ice crystals within cloud reduces its optical depth, which reduces its albedo (Storelvmo et al., 2015). In addition, the formation of ice particles is an important precipitation triggering process (Boucher et al., 2013).

The state dependence of cloud-phase feedbacks is a crucial factor in the evolution of Earth's climate sensitivity (Bjordal et al., 2020). For example, present-day climate models predict that global warming

leads to less cloud glaciation, thicker average optical depth and increased average albedo (Storelvmo et al., 2015). The increased cloud albedo exerts a cooling effect on the climate, which counteracts warming forcers such as increases in greenhouse gases, thus acting to maintain stability (Murray et al., 2020; Storelvmo, 2017). Recent observations and insights from sensitivity studies demonstrate that the presence of INPs results in more mixed-phase cloud, and acts to suppress the cloud albedo cooling feedback (Murray et al., 2020; Tan et al., 2016). A pioneering model that includes Kfs parameterization, using modern mineralogy distribution (trace amounts of Kfs), shows significantly reduced cloud albedo with warming on regional scales compared to modelling without INPs (Thürmer et al., 2019).

Mineral aerosols and clouds

Mineral dust accounts for around half the aerosol in the modern atmosphere by mass (Knippertz and Todd, 2012), and a greater proportion existed in pre-industrial times (Carslaw et al., 2017). The dust cycle is characterized by primary emission events (dust storms), dispersion mainly through the lower troposphere, and eventual removal by dry- or wet-deposition (Shao et al., 2011). Clay minerals form at the Earth's surface which results in a thin, yet near-ubiquitous, barrier between fresh rocks and the atmosphere. This is why clay dominates today's atmospheric dust and has defined the normal atmospheric mineralogical regime since at least the Neoproterozoic (Pankhurst, 2017).

Relative to other minerals, Kfs exhibits extraordinary ice-nucleation properties and is identified as playing a key role in cloud microphysics since it nucleates ice at about -15°C (Atkinson *et al.* 2013; Harrison *et al.* 2019). Perthite (Kfs with a micro-texture of sodic feldspar lamellae) is the exceptional form, as this texture leads to a high density of active sites for ice nucleation (Whale et al., 2017). Perthite is characteristic of granitic intrusions which are common, yet unevenly distributed, within the Earth's continental crust (Coldwell and Pankhurst, 2019). Kfs is comparatively stable at surface conditions (White et al., 2001) yet in the presence of water it will eventually break down, which is why Kfs comprises only ~3% of modern mineral dust (Atkinson et al., 2013), mostly emitted from arid regions where chemical weathering is slowest (Pankhurst, 2017), and is present primarily in coarse mode dust (Thürmer et al., 2019). Knowledge of the ice-nucleating efficiency of minerals is far from complete, and there is evidence that members of the pyroxene family may exhibit comparatively high ice-activity (Jahn *et al.* 2019; Maters *et al.* 2019). However, the overall contribution of pyroxenes to

ejecta blankets is very low Coldwell & Pankhurst (2019), owing to their paucity in sedimentary successions and because they are more common in deeper parts of the crystalline crust. As such they are not a focus of this study.

A model for meteorite effects on climate

When a large meteorite hits the Earth and transfers its kinetic energy into the lithosphere, the meteorite itself is vaporized, local crust melts, and extreme volumes of dust and secondary particulates are ejected into the full atmospheric column as part of the cratering process and immediate aftermath (Toon *et al.* 1997). In a geological instant, normal terrestrial dust cycle processes (Fig. 4a) and the role of clouds on the climate are overshadowed by the direct effects of the impact, particularly from stratospheric dust (Fig. 4b). Dust directly blocks incoming solar radiation, causing dimmer and colder conditions at the Earth's surface. The fine dust resides for days-months in the atmosphere (over a year for a Chicxulub-sized impact). As the primary dust, and secondary particulates such as soot, settle and wash out of the atmosphere, the direct cooling diminishes and more sunlight reaches the Earth's surface. The Earth returns to its pre-impact equilibrium temperature (Toon *et al.* 1997).

As Impact Winter wanes, cloud regains its importance on direct radiative forcing and its role in balancing the Earth's energy budget. The normal mechanisms and fluxes of the terrestrial dust cycle also resume. Mineral particles are entrained by surface winds, and the bulk of atmospheric dust transportation is restricted to the troposphere. However, now a defining portion of that dust is composed of minerals from the meteorite ejecta blanket. This means the aerosol mineralogy may have changed, and so potentially affect the properties of average low-altitude cloud differently.

Kfs-poor ejecta blankets are predicted to have negligible effect upon cloud glaciation because their mineral aerosols have similar ice-nucleating efficiency to clay (Fig. 4b, see Atkinson *et al.* 2013; Harrison *et al.* 2019). Therefore, low-altitude warm-clouds remain composed primarily of water droplets, remain optically thick with high-albedos, continue to produce a net cooling effect on the Earth's climate, and all else being equal, the Earth climate system rebalances towards its pre-impact equilibrium (Fig. 4b to 4a). Clouds' responses to warming forcers (e.g. an increase in atmospheric greenhouse gases) are expected to operate in the same manner to those during periods without any

ejecta blanket influence (i.e. the modern pre-industrial climate system, Storelvmo *et al.* 2015; Bjordal *et al.* 2020).

In contrast, Kfs-rich ejecta blankets are likely to increase the importance of dust in the climate system by supplying particles with powerful ice-nucleation efficiency to the troposphere. In this scenario (Fig. 4C), cloud conditions that would have previously been ice-free or ice-poor at temperatures below -15 °C are now far more likely to be glaciated. The increased proportion of ice particles in average tropospheric cloud reduces their optical thickness and albedo, resulting in increased surface temperatures. Above the dust transportation level, high-altitude cloud is comparatively unaffected and its small net warming effect continues. Therefore, the overall general affects that can be expected from Kfs-rich ejecta blankets are 1) for the planet to warm past the pre-impact climate equilibrium due to reduced global albedo and 2) by acting to keep a higher proportion of ice at higher temperatures, a weakening of the state-dependent cloud albedo feedback. Over time, the amount of Kfs will decrease due to weathering, and return atmospheric mineralogy to normal clay-dominated conditions (Coldwell and Pankhurst 2019). Hence, the proposed effects on clouds and climate will reduce over weathering timescales of tens to hundreds of thousands of years (Fig. 4c to 4a).

Complexity and uncertainty in the climate system response

The model proposed to explain the potential effects of Kfs-rich impact ejecta blankets on paleoclimate is derived from our understanding of how factors influencing cloud state modulate the present-day climate. For decades global climate model predictions for enhanced climate sensitivity under warming conditions ranged from ~2-4.5 °C yet cloud feedback responses were not well captured (Bjordal *et al.* 2020). Now modelling shows that the response of clouds under warming conditions from increasing greenhouse gas concentrations has a strong influence on climate sensitivity. Models appropriately capturing cloud albedo feedbacks predict increases in equilibrium climate sensitivity between 6.5-7.1 °C (95% confidence interval) under a 4 times increase in CO_2 concentration with respect to pre-industrial conditions (Bjordal *et al.* 2020) This modelling of warming of the modern atmosphere predicts mixed-phase cloud to lose ice proportion and increase supercooled liquid fraction, initially suppressing global warming via cloud albedo cooling feedback. When all the ice is converted to liquid, this cooling feedback is exhausted, after which net warming cloud feedbacks dominate.

The presence of INPs in supercooled clouds promotes glaciation, and this state change is shown to significantly reduce mixed-phase cloud reflectivity (Murray et al., 2021), at local scales by hundreds of watts per square meter (Vergara-Temprado *et al.* 2018). The retention of ice at higher temperatures contributes a dampening of the cloud albedo feedback under global warming (Tan *et al.* 2016). This means it is plausible that the extreme abundance and proportions of Kfs in the atmosphere from a meteorite ejecta blanket, relative to modern mineral dust, could significantly reduce the initial cloud albedo cooling feedback stage by promoting glaciation—or rather resisting deglaciation—in mixed-phase cloud conditions below -15 °C. By inhibiting deglaciation, relative to normal scenarios where INP efficiency is far lower, and limiting a key negative feedback, it follows that one affect would be increased climate sensitivity.

Estimating specific climate equilibrium temperatures from these meteorite-induced Kfs effects is problematic due to the complexities and uncertainties surrounding the climate system. In the first instance, clouds can produce a range of feedbacks depending on their abundance, type and latitudinal position (Ceppi *et al.* 2017; Bjordal *et al.* 2020). For example, as the planet warms tropical tropospheric convection mixes saturated air to higher altitudes. This increases the height of free-tropospheric clouds, which means they are colder and absorb more long-wave radiation emitted from the Earth's surface (Ceppi *et al.* 2017). This results in a positive (warming) feedback. Warming at mid- to high-latitudes sees a variety of antagonistic processes reduce the amount of low-altitude cloud, which results in a positive (warming) feedback (Ceppi *et al.* 2017). The interplay between cloud amount, cloud type and how these factors will change in the presence of INPs and their efficiency is poorly understood in present-day climate models. Therefore, it remains unclear how the manifest range of cloud processes and feedback mechanisms may interact under an extreme meteorite induced INP scenario.

In addition to the uncertainties based on present-day climate models, deep time sees a variety of continental arrangements, ocean circulation patterns and physical geography. These factors have likely played roles in modulating atmospheric patterns, affecting average cloud type distributions as part of global climate, and so also in governing the climate sensitivity to a variety of forcing over time. The spectrum of Earth system configurations through geological time could potentially result in climate states that respond differently to modern-day climate scenarios. Furthermore, secular

changes in the evolution of life affecting biosphere structure also influence how changes to climate are reflected by extinction rate and lethality of discrete events (Newman and Eble 1999).

Therefore, it is striking that despite the variety of Earth's configurations, climate states, and potential responses from life, every Kfs-rich ejecta blanket over the past 600 Myr coincides with a severe extinction event (Figs 1 and 2). This suggests that Kfs ejecta blankets had a fundamental role in destabilizing the biosphere each time, regardless of those Earth systems' specific configurations.

Atmospheric change and Earth Crises

The atmosphere is a first-order control on climate. It is linked to both terrestrial and marine biospheres, and through element cycling and gas exchange it regulates all ecosystems across the planet. The most severe extinction episodes include both terrestrial and marine biospheres (Bond and Grasby 2017). This strongly suggests the driver of severe extinction episodes is a critical change in atmospheric function.

Reduced atmospheric shielding of solar radiation has been linked to increased levels of UV-B radiation reaching the Earth's surface, resulting in DNA damage and mass extinctions (Marshall *et al.* 2020). Warming of the atmosphere has been linked to a variety of kill mechanisms including marine anoxia and acidification (Bond and Grasby 2017). Geologic records demonstrate aridification, mass wasting and increased biomass burning are also linked to climate warming (Benton and Newell 2014).

Global mean cloud albedo during much of Earth history could have been twice as sensitive to changes in aerosol emissions as it is today, owing to the low concentration of aerosol particles under pre-industrial conditions (Carslaw *et al.* 2017). Suppression of the cloud cooling feedback mechanism makes the climate system more sensitive to other forcers and so permits otherwise buffered forcers to affect significant climate change. For example, Large Igneous Provinces (LIPs) are argued to drive mass extinctions by their emission of large volumes of greenhouse gases (Bond and Grasby 2017). On longer timescales extending to over 1 Myr, extensive weathering of basaltic lava at LIP scales is suggested to accelerate global CO_2 drawdown and represent an important cooling forcer (Dessert *et al.* 2001). However, many LIPs, including the world's largest, are not associated with mass extinctions (Kelley 2007). The consequence of a Kfs-rich ejecta blanket that is emplaced during the development

of a LIP may be to suddenly suppress the atmospheric buffer on global temperature rise. For the same volume and rate of greenhouse gas input, initial warming from LIP emissions will likely be faster and reach higher temperatures. We note that those mass extinctions that are most clearly associated with LIPs (end-Permian; end-Triassic; end-Cretaceous) are also associated with Kfs-rich ejecta blankets. This aspect of our interpretation may explain why a variety of Earth system phenomena that are generally associated with comparatively stable ecosystems, can also be seen occasionally to drive and/or contribute significantly to environmental catastrophes.

Conclusions and implications

A synthesis of 33 meteorite impacts and extinction intensities over the past 600 Myr demonstrates that it is not the size of impact but the Kfs content of the ejecta blanket that correlates between meteorite impacts and mass extinction events. The pattern accounts for 11 extinction episodes across the history of multicellular life including the majority of the most severe examples, and also the Acritarch crisis ca. 580 Ma. Meteorite impacts that hit Kfs-poor rocks correspond only to background extinction intensity.

We propose a conceptual model whereby Kfs-rich ejecta blankets provide a source of efficient ice nucleating particles to the atmosphere and have a period of influence on the Earth system for tens-hundreds of thousands of years. Due to this change in aerosol mineralogy, mixed-phase clouds contain a higher proportion of ice crystals. This makes them optically thinner and reduces the contribution of cloud albedo to cooling, which produces a relative warming effect at the Earth's surface. Enhanced Kfs cloud glaciation also suppresses cloud stabilizing feedbacks (resisting the deglaciation of cloud which results in lower albedo), which makes the climate more sensitive to other factors, e.g. high rates of greenhouse gas emissions. As a result, otherwise buffered (and accordingly, not as influential) Earth system phenomena have disproportionately strong effects on the climate. The proposed model explains how Kfs, which is common in the Earth's subsurface and not directly harmful to life, when present as an ongoing high proportion of atmospheric mineral dust correlates so strongly with mass extinctions through time. Moreover, it may help explain why other Earth system phenomena can have markedly different effects on climate at different times through Earth's history.

Kfs is recognised as the most important mineral aerosol in today's climate despite its present scarcity. It's importance through deep time is now also apparent. The available evidence suggests that until modern times, only meteorite impacts can change atmospheric mineralogy with such (geological) suddenness and persistence. However, anthropogenic activities may represent similar climate forcing with rapid input of aerosols into the atmosphere that influence cloud dynamics.

Data availability

All raw data are available in the cited references. Calculations, including scripts, are provided in the online supplement.

Author contributions

MJP: Conceptualisation, methodology, investigation, formal analysis, writing – original draft and review and editing, visualisation

CJS: Conceptualisation, investigation, writing – original draft and review and editing, visualisation

BCC: Conceptualisation, investigation, writing – original draft and review and editing

Figure Captions

Fig. 1. Comparison of meteorite impact stratigraphy, and extinction intensity of well-resolved marine genera. a) Impact database of 33 largest and best-dated impacts in the past 600 million years (Coldwell and Pankhurst 2019). Transient crater diameter ≥10 km and age precision better than ±8 Myr. Updated from Coldwell and Pankhurst (2019) using revised age data (Schmieder and Kring 2019) and plotted by size and K-feldspar Factor (KFF) of target rocks. Fifteen of 33 ejecta blankets are predicted to have caused long-term interruptions of the normal atmospheric ice-nucleation regime. b) Extinction intensity for the entire duration of multicellular life highlights times of global environmental crises. Timing of acritarch crisis also shown. Each Kfs-rich ejecta blanket corresponds to an Earth crisis, and accounts for the majority of severe spikes in extinction intensity, including almost all since ~250 Ma when both records are most complete. See SFig. 1 for KFF timeline, meteorite impact labels and named extinction events.

Fig. 2. Mass extinction events and extinction intensity correspond to Kfs availability to the troposphere, not larger impact size. Only those craters with age precision that places the date of

meteorite impact within a single geological substage are plotted, which provide 7 Kfs-rich and 6 Kfs-poor events. Extinction intensity of marine genera is expressed as percentage change from previous to highlight changes from substage to substage. Substages marked by an extinction event are labelled. See Supp. for plots including less precise database entries, and other projections of extinction data.

Fig. 3. Time-series event analysis of Earth crises, meteorite impacts, and ejecta blanket Kfs content, from ca. 565 Ma to present. The timing of every Kfs-rich ejecta blanket plausibly coincides with an extinction episode. The most precisely dated subset (see Fig. 2 and Supp.) returns 100% simultaneity. In contrast, just 1/18 ejecta blankets that did not cause an increase in Kfs availability could possibly overlap an extinction event, and the most precisely dated subset (Fig. 2) has 0% simultaneity. ‡End Triassic extinction is codified into both the Upper Norian and Rhaetian.

Fig. 4. The enhanced cloud glaciation hypothesis for driving accelerated global climate and evolutionary change. a) Normal clay regime results in low and well-buffered atmospheric ice nucleation for ~99% of the past 600 Myr. Short and long wave radiation are in dynamic balance, modulated by warm and cold clouds. b) Meteorite impact generates Impact Winter, and short term cooling over months. Low Kfs ejecta blankets have negligible effect on atmospheric ice nucleation. c) The presence of a Kfs-rich ejecta blanket increases the ice nucleation efficiency of mineral aerosol as part of the normal dust cycle flux, and results in enhanced cloud glaciation. The optical depth of low cloud is thinned and its albedo reduced, resulting in net warming. The cloud albedo feedback mechanism is suppressed, the climate sensitized, and the Earth is made more vulnerable to other climate forcers such as greenhouse gas concentrations. Effects of Kfs aerosol diminish with weathering, which eventually reverts the surface and atmospheric mineralogy back to a clay-dominated regime. The climate instability, including inducement of kill mechanisms, effects accelerated ecosystem change and biological turnover, recorded most prominently in the fossil record as mass extinctions.

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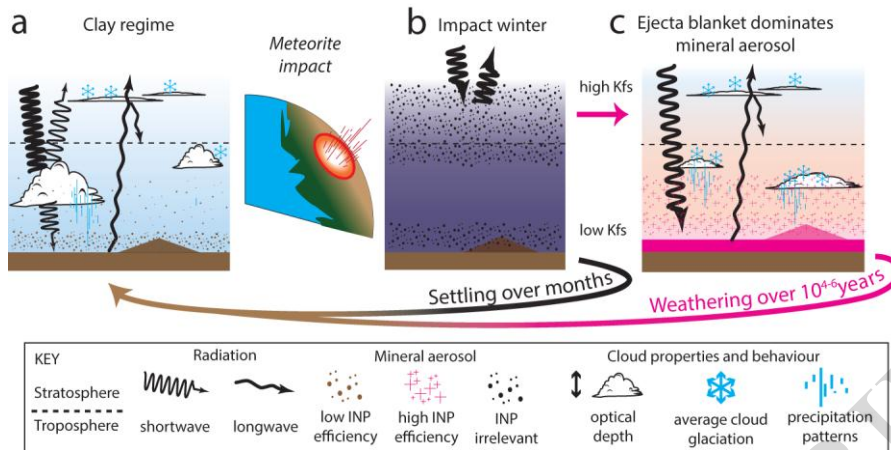
Figure 1

Figure 2

Figure 3

Figure 4