Meteorites that produce K-feldspar-rich ejecta blankets correspond to mass extinctions.

**Authors (ORCID)**

\*M. J. Pankhurst1,2 : 0000-0001-6844-9822

C. J. Stevenson3 : 0000-0003-0406-9892

B. C. Coldwell1,2 : 0000-0001-9240-6240

**Affiliations**

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

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

3Earth, 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 <100 years, whereas ejecta blankets persist for 103-105 years. Here we show that only meteorite impacts that emplaced ejecta blankets rich in K-feldspar correlate to Earth-system crises (n=11, p<0.000005). K-feldspar 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. We propose a conceptual model whereby each K-feldspar rich ejecta blanket caused a departure from the normal function of atmospheric dust in the climate system. The dramatically increased proportion of K-feldspar is posited to have had two key effects on cloud dynamics: 1) reducing the average albedo of mixed-phase cloud, which effected a hotter global climate; 2) weakening of the cloud albedo feedback, which increased climate sensitivity. These mechanisms offer an explanation as to why Kfs, an otherwise benign mineral, is correlated with mass extinction events. It is Kfs’ ability to influence cloud dynamics, and in turn, the global climate that can profoundly destabilize the biosphere. This model may also explain why many well-established short-term kill mechanisms only variably correlate with extinction events through geological time: they coincide with these rare periods of climate destabilization by atmospheric Kfs. Together, cascading effects were catastrophic for life: every K-feldspar rich impact corresponds to a severe extinction episode over the past 600 Myrs.

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 phenomena (Toon et al., 1997) whereby impact ejecta blocks 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 Myrs. 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 blankets the Earth’s surface has 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 likely 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 Myrs. 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 eighteen 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 don’t. 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, 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) does 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 CO2 (Kaiho *et al.* 2001; Ohno *et al.* 2014; Kaiho and Oshima 2017).

Whilst not chemically gregarious, Kfs mineral aerosols have been shown to be the most powerful ice-nucleating particle in the atmosphere (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 affects 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 (INP’s) in the atmosphere modulate cloud properties between these warm and cold end-members (Murray et al., 2020). Supercooled water freezes homogeneously at -39°C yet if INP’s 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 vapour or 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 gasses, thus acting to maintain stability (Murray et al., 2020; Storelvmo, 2017). Recent observations and insights from sensitivity studies demonstrate that the presence of INP’s 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 characterised 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 polymorph, 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 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 breakdown, 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 o 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). 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 defined by a mineralogy 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 its 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.

*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 climate sensitivity between 6.5-7.1 °C (95% confidence interval) under a 4 times increase in CO2 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 so limiting a key negative feedback, it follows that one effect 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 Myrs coincides with a severe extinction event (Figs 1 and 2). This suggests that Kfs ejecta blankets had a fundamental role in destabilizing the biosphere every time, whatever the Earth’s configuration.

*Atmospheric change and Earth Crises*

The atmosphere is a first-order control on climate. It is linked into 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, LIPs are argued to drive mass extinctions by their emission of large volumes of greenhouse gasses (Bond and Grasby 2017). However, many, 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 is to suddenly suppress the atmospheric buffer on global temperature. For the same volume and rate of greenhouse gas input, 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 occasionally drive and/or contribute significantly to environmental catastrophes.

**Conclusions and implications**

A synthesis of 33 meteorite impacts and extinction intensities over the past 600 Myrs demonstrates that it is 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 higher 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, benign) 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. ǂEnd 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 Myrs. 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.

**References**

Alvarez, L.W., Alvarez, W., Asaro, F. and Michel, H.V. 1980. Extraterrestrial Cause for the Cretaceous-Tertiary Extinction. *Science*, **208**, 1095–1108, https://doi.org/10.1126/science.208.4448.1095.

Atkinson, J.D., Murray, B.J., et al. 2013. The importance of feldspar for ice nucleation by mineral dust in mixed-phase clouds. *Nature*, **498**, 355–358, https://doi.org/10.1038/nature12278.

Bambach, R.K. 2006. Phanerozoic biodiversity mass extinctions. *Annu. Rev. Earth Planet. Sci.*, **34**, 127–155.

Benton, M.J. and Newell, A.J. 2014. Impacts of global warming on Permo-Triassic terrestrial ecosystems. *Gondwana Research*, **25**, 1308–1337, http://dx.doi.org/10.1016/j.gr.2012.12.010.

Bjordal, J., Storelvmo, T., Alterskjær, K. and Carlsen, T. 2020. Equilibrium climate sensitivity above 5 °C plausible due to state-dependent cloud feedback. *Nature Geoscience*, **13**, 718–721, https://doi.org/10.1038/s41561-020-00649-1.

Bond, D.P.G. and Grasby, S.E. 2017. On the causes of mass extinctions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **478**, 3–29, https://doi.org/10.1016/j.palaeo.2016.11.005.

Boucher, O., Randall, D., et al. 2013. Clouds and aerosols. *In*: *Climate Change 2013: The Physical Science Basis.* 571–657.

Carslaw, K.S., Gordon, H., Hamilton, D.S., Johnson, J.S., Regayre, L.A., Yoshioka, M. and Pringle, K.J. 2017. Aerosols in the Pre-industrial Atmosphere. *Current Climate Change Reports*, **3**, 1–15, https://doi.org/10.1007/s40641-017-0061-2.

Ceppi, P., Brient, F., Zelinka, M.D. and Hartmann, D.L. 2017. Cloud feedback mechanisms and their representation in global climate models. *WIREs Climate Change*, **8**, e465, https://doi.org/10.1002/wcc.465.

Coldwell, B.C. and Pankhurst, M.J. 2019. Evaluating the influence of meteorite impact events on global potassium feldspar availability to the atmosphere since 600 Ma. *Journal of the Geological Society*, **176**, 209–224, https://doi.org/10.1144/jgs2018-084.

Foote, M. 2003. Origination and Extinction through the Phanerozoic: A New Approach. *The Journal of Geology*, **111**, 125–148, https://doi.org/10.1086/345841.

Grey, K., Walter, M.R. and Calver, C.R. 2003. Neoproterozoic biotic diversification: Snowball Earth or aftermath of the Acraman impact? *Geology*, **31**, 459–462, https://doi.org/10.1130/0091-7613(2003)031<0459:nbdseo>2.0.co;2.

Harrison, A.D., Lever, K., et al. 2019. The ice-nucleating ability of quartz immersed in water and its atmospheric importance compared to K-feldspar. *Atmospheric Chemistry and Physics*, **19**, 11343–11361, https://doi.org/10.5194/acp-19-11343-2019.

Holland, S.M. 2020. The Stratigraphy of Mass Extinctions and Recoveries. *Annual Review of Earth and Planetary Sciences*, **48**, 75–97, https://doi.org/10.1146/annurev-earth-071719-054827.

Hull, P.M., Bornemann, A., et al. 2020. On impact and volcanism across the Cretaceous-Paleogene boundary. *Science*, **367**, 266–272, https://doi.org/10.1126/science.aay5055.

Jahn, L.G., Fahy, W.D., Williams, D.B. and Sullivan, R.C. 2019. Role of Feldspar and Pyroxene Minerals in the Ice Nucleating Ability of Three Volcanic Ashes. *ACS Earth and Space Chemistry*, **3**, 626–636, https://doi.org/10.1021/acsearthspacechem.9b00004.

Kaiho, K. and Oshima, N. 2017. Site of asteroid impact changed the history of life on Earth: the low probability of mass extinction. *Scientific Reports*, **7**, 14855, https://doi.org/10.1038/s41598-017-14199-x.

Kaiho, K., Kajiwara, Y., et al. 2001. End-Permian catastrophe by a bolide impact: Evidence of a gigantic release of sulfur from the mantle. *Geology*, **29**, 815–818, https://doi.org/10.1130/0091-7613(2001)029<0815:epcbab>2.0.co;2.

Kauffinan, E.G. 1994. Common Patterns of Mass Extinction, Survival, and Recovery in Marine Environments: What Do They Tell Us About the Future? *The Paleontological Society Special Publications*, **7**, 437–466, https://doi.org/10.1017/S2475262200009709.

Kelley, S. 2007. The geochronology of large igneous provinces, terrestrial impact craters, and their relationship to mass extinctions on Earth. *Journal of the Geological Society*, **164**, 923–936, https://doi.org/10.1144/0016-76492007-026.

Knippertz, P. and Todd, M.C. 2012. Mineral dust aerosols over the Sahara: Meteorological controls on emission and transport and implications for modeling. *Reviews of Geophysics*, **50**, RG1007, https://doi.org/10.1029/2011RG000362.

Kocsis, Á.T., Reddin, C.J., Alroy, J. and Kiessling, W. 2019. The r package divDyn for quantifying diversity dynamics using fossil sampling data. *Methods in Ecology and Evolution*, **10**, 735–743, https://doi.org/10.1111/2041-210X.13161.

Marshall, J.E.A., Lakin, J., Troth, I. and Wallace-Johnson, S.M. 2020. UV-B radiation was the Devonian-Carboniferous boundary terrestrial extinction kill mechanism. *Science Advances*, **6**, eaba0768, https://doi.org/10.1126/sciadv.aba0768.

Maters, E.C., Dingwell, D.B., Cimarelli, C., Müller, D., Whale, T.F. and Murray, B.J. 2019. The importance of crystalline phases in ice nucleation by volcanic ash. *Atmospheric Chemistry and Physics*, **19**, 5451–5465, https://doi.org/10.5194/acp-19-5451-2019.

Mohammed, S.M.O., Brandt, K., Gray, N.D., White, M.L. and Manning, D. a. C. 2014. Comparison of silicate minerals as sources of potassium for plant nutrition in sandy soil. *European Journal of Soil Science*, **65**, 653–662, https://doi.org/10.1111/ejss.12172.

Murray, B.J., O’sullivan, D., Atkinson, J.D. and Webb, M.E. 2012. Ice nucleation by particles immersed in supercooled cloud droplets. *Chemical Society reviews*, **41**, 6519–6554.

Murray, B.J., Carslaw, K.S. and Field, P.R. 2020. Opinion: Cloud-phase climate feedback and the importance of ice-nucleating particles. *Atmospheric Chemistry and Physics Discussions*, 1–23, https://doi.org/10.5194/acp-2020-852.

Newman, M.E.J. and Eble, G.J. 1999. Decline in Extinction Rates and Scale Invariance in the Fossil Record. *Paleobiology*, **25**, 434–439.

Ohno, S., Kadono, T., et al. 2014. Production of sulphate-rich vapour during the Chicxulub impact and implications for ocean acidification. *Nature Geoscience*, **7**, 279–282, https://doi.org/10.1038/ngeo2095.

Pankhurst, M.J. 2017. Atmospheric K-feldspar as a potential climate modulating agent through geologic time. *Geology*, **45**, 379–382, https://doi.org/10.1130/g38684.1.

Rohde, R.A. and Muller, R.A. 2005. Cycles in fossil diversity. *Nature*, **434**, 208–210, https://doi.org/10.1038/nature03339.

Schmieder, M. and Kring, D.A. 2019. Earth’s Impact Events Through Geologic Time: A List of Recommended Ages for Terrestrial Impact Structures and Deposits. *Astrobiology*, **20**, 91–141, https://doi.org/10.1089/ast.2019.2085.

Sepkoski, J.J. 1986. Phanerozoic Overview of Mass Extinction. *In*: Raup, D. M. and Jablonski, D. (eds) *Patterns and Processes in the History of Life*. Dahlem Workshop Reports, 277–295., https://doi.org/10.1007/978-3-642-70831-2\_15.

Shao, Y., Wyrwoll, K.-H., et al. 2011. Dust cycle: An emerging core theme in Earth system science. *Aeolian Research*, **2**, 181–204, http://dx.doi.org/10.1016/j.aeolia.2011.02.001.

Siegmund, J.F., Siegmund, N. and Donner, R.V. 2017. CoinCalc—A new R package for quantifying simultaneities of event series. *Computers & Geosciences*, **98**, 64–72, https://doi.org/10.1016/j.cageo.2016.10.004.

Storelvmo, T. 2017. Aerosol Effects on Climate via Mixed-Phase and Ice Clouds. *Annual Review of Earth and Planetary Sciences*, **45**, 199–222.

Storelvmo, T., Tan, I. and Korolev, A.V. 2015. Cloud Phase Changes Induced by CO2 Warming—a Powerful yet Poorly Constrained Cloud-Climate Feedback. *Current Climate Change Reports*, **1**, 288–296, https://doi.org/10.1007/s40641-015-0026-2.

Tan, I., Storelvmo, T. and Zelinka, M.D. 2016. Observational constraints on mixed-phase clouds imply higher climate sensitivity. *Science*, **352**, 224–227.

The Paleobiology Database. 2021https://www.gbif.org/dataset/c33ce2f2-c3cc-43a5-a380-fe4526d63650.

Thürmer, K., Friddle, R.W., Wheeler, L.B., Bartelt, N.C., Roesler, E.L. and Kolasinski, R. 2019. *Deciphering Atmospheric Ice Nucleation Using Molecular-Scale Microscopy.* **SAND2019-11159**, https://doi.org/10.2172/1569351.

Tohver, E., Lana, C., et al. 2012. Geochronological constraints on the age of a Permo–Triassic impact event: U–Pb and 40Ar/39Ar results for the 40 km Araguainha structure of central Brazil. *Geochimica Et Cosmochimica Acta*, **86**, 214–227, https://doi.org/10.1016/j.gca.2012.03.005.

Toon, O.B., Zahnle, K., Morrison, D., Turco, R.P. and Covey, C. 1997. Environmental perturbations caused by the impacts of asteroids and comets. *Reviews of Geophysics*, **35**, 41–78, https://doi.org/10.1029/96RG03038.

Vergara-Temprado, J., Murray, B.J., et al. 2017. Contribution of feldspar and marine organic aerosols to global ice nucleating particle concentrations. *Atmospheric Chemistry and Physics*, **17**, 3637–3658, https://doi.org/10.5194/acp-17-3637-2017.

Vergara-Temprado, J., Miltenberger, A.K., et al. 2018. Strong control of Southern Ocean cloud reflectivity by ice-nucleating particles. *Proceedings of the National Academy of Sciences*, **115**, 2687–2692, https://doi.org/10.1073/pnas.1721627115.

Whale, T.F., Holden, M.A., Kulak, A.N., Kim, Y.-Y., Meldrum, F.C., Christenson, H.K. and Murray, B.J. 2017. The role of phase separation and related topography in the exceptional ice-nucleating ability of alkali feldspars. *Physical Chemistry Chemical Physics*, **19**, 31186–31193.

White, A.F., Bullen, T.D., Schulz, M.S., Blum, A.E., Huntington, T.G. and Peters, N.E. 2001. Differential rates of feldspar weathering in granitic regoliths. *Geochimica et Cosmochimica Acta*, **65**, 847–869, https://doi.org/10.1016/S0016-7037(00)00577-9.

**Figures and Tables**



**Figure 1. Comparison of meteorite impact stratigraphy, and extinction intensity of well-resolved marine genera.** A) Impact database of 32 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 32 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.



**Figure 2. Mass extinction events and intensity correspond to KFF, not 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.



**Figure 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. ǂEnd Triassic extinction is codified into both the Upper Norian and Rhaetian.



**Figure 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 Myrs. 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.