GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G46733.1

Manuscript received 9 July 2019
Revised manuscript received 10 February 2020
Manuscript accepted 27 February 2020

Published online 29 April 2020

The spatial flux of Earth's meteorite falls found via Antarctic data

G.W. Evatt[1], A.R.D. Smedley[1], K.H. Joy[2], L. Hunter[1], W.H. Tey[3], I.D. Abrahams[1,4] and L. Gerrish[5]
[1]Department of Mathematics, University of Manchester, Manchester M13 9PL, UK
[2]Department of Earth and Environmental Sciences, University of Manchester, Manchester M13 9PL, UK
[3]Department of Mathematics, Imperial College London, London SW7 2AZ, UK
[4]Isaac Newton Institute for Mathematical Sciences, University of Cambridge, Cambridge CB3 0EH, UK
[5]British Antarctic Survey, Cambridge CB3 0ET, UK

ABSTRACT

Contemporary calculations for the flux of extraterrestrial material falling to the Earth's surface (each event referred to as a "fall") rely upon either short-duration fireball monitoring networks or spatially limited ground-based meteorite searches. To date, making accurate fall flux estimates from the much-documented meteorite stranding zones of Antarctica has been prohibited due to complicating glacial ice dynamics and difficulties in pairing together distinct meteorite samples originating from the same fall. Through glaciological analysis and use of meteorite collection data, we demonstrate how to overcome these barriers to making flux estimates. Furthermore, by showing that a clear latitudinal variation in fall frequencies exists and then modeling its mathematical form, we are able to expand our Antarctic result to a global setting. In this way, we hereby provide the most accurate contemporary fall flux estimates for anywhere on Earth. Inverting the methodology provides a valuable tool for planning new meteorite collection missions to unvisited regions of Antarctica. Our modeling also enables a reassessment of the risk to Earth from larger meteoroid impacts—now 12% higher at the equator and 27% lower at the poles than if the flux were globally uniform.

INTRODUCTION

Extraterrestrial material that falls to Earth is heated, ablated, and can break up during its passage through the atmosphere. Any surviving rock fragments that reach Earth's surface are termed meteorites and provide a tangible link to the evolution and composition of the solar system at different stages in its history (Joy et al., 2016; Schmitz et al., 2016; DeMeo, 2017; Heck et al., 2017;). Present estimates for the flux of extraterrestrial material falling to Earth's surface rely upon either short-duration fireball monitoring networks (Halliday et al., 1996; Bland et al., 2012; Howie et al., 2017) or spatially limited ground-based meteorite searches from hot deserts (Bland et al., 1996; Gattacceca et al., 2011; Hutzler et al., 2016). Both approaches have their own advantages, and they each contribute to assessing potential hazards to life from larger impacts (Brown et al., 2013). However, a distinct benefit of the hot-desert-search approach is that retrieved samples enable us to quantify the transfer of solar system material to the Earth-Moon system across a wide range of sample masses without having to estimate the masses from fireball brightness.

Yet despite the benefits of controlled hot desert searches, the absolute number of searches and the number of meteorite samples collected within those searches are dwarfed by the number of controlled Antarctic searches that have taken place and the number of meteorites collected within them (MetBull, 2018). These Antarctic samples are collected from meteorite stranding zones (MSZs) (Folco et al., 2002; Harvey et al., 2014; Righter et al., 2014; Miao et al., 2018), which are blue ice areas typically located near mountainous regions of the continent. But until now, this major resource of near-pristine material has not been usable to accurately estimate the associated flux of extraterrestrial material to Earth. In part, this has been due to pairing uncertainties between meteorite samples, but it is due primarily to the complex mechanics by which meteorites are concentrated onto the surface of the MSZs (Zolensky, 1998; Bland, 2005; Zolensky et al., 2006): both from above by direct infall, and from below by the ablating ice flow releasing any entrained meteorites (Evatt et al., 2016).

To make use of the large number of collected Antarctic meteorite samples in order to estimate the flux of extraterrestrial material arriving on Earth, we constructed a mathematical model in stages and compared intermediate outputs to results from the literature. We first modeled the conservation of mass of a MSZ to determine the effective catchment area, which we then used to help determine the associated (glacial) flux of meteorites through a MSZ. With this, we were then able to determine a local extraterrestrial flux of meteorites. To compare with non-Antarctic flux estimates, we developed a model for capturing latitudinal variations of the flux, and demonstrate how well it fits to fireball observations. The resulting comparison of fluxes between geographically distinct regions also provides us with a data-driven approach to calculating Antarctic meteorite pairing factors; i.e., the number of paired-together meteorite fragments originating from the same fall. Finally, we discuss the implications of our model; in particular, how the risk to Earth from larger impact events has a strong latitudinal variation.

METHODS AND RESULTS

To overcome the barriers to estimating Earth's present day fall flux via the untapped resource of Antarctic meteorite data, we analyzed glaciological and meteoritical data from 45 documented Antarctic MSZs, but focused upon the results from 13 systematically searched areas. These 13 areas were selected because they each have > 100 finds, a well-defined spatial extent, and together sample a range of Antarctic localities (Table 1; Fig. 1).

The first step was to determine the effective surface area of each MSZ, which is the surface area of the MSZ plus the upstream surface

CITATION: Evatt, G.W., et al., 2020, The spatial flux of Earth's meteorite falls found via Antarctic data: Geology, v. 48, p. 683–687, https://doi.org/10.1130/G46733.1

TABLE 1. SUMMARY OF "HIGH QUALITY" BLUE ICE METEORITE STRANDING ZONE DATA, ANTARCTICA

Location name	Geographic coordinates	Altitude (m)	Area (km^2)	Ablation ($kg\ m^{-2}\ yr^{-1}$)	SMB ($kg\ m^{-2}\ yr^{-1}$)	Residency time (k.y.)	Ice flow velocity ($m\ yr^{-1}$)	Flux of meteorites >50 g ($km^{-2}\ m.y.^{-1}$)	Number of finds
Pecora Escarpment [PCA]	85°39′54″S 68°25′30″W	1598	112.7	77.4	98.3	4.08	2.30	256.75	633
LaPaz Icefield [LAP]	86°20′14″S 70°43′47″W	1731	390.7	68.3	66.4	3.27	3.67	164.39	1675
Allan Hills Main Icefield [ALH1]	76°41′05″S 159°15′55″E	2010	88.7	21.9	36.7	24.89	1.00	56.25	868
Allan Hills Near Western Icefield [ALH2]	76°44′27″S 158°45′13″E	2080	24.0	34.1	19.4	24.89	1.00	82.06	245
Allan Hills Mid Western Icefield [ALH3]	76°50′37″S 158°21′48″E	2150	58.1	32.6	14.6	24.89	1.00	12.20	127
Allan Hills Far Western Icefield [ALH4]	76°54′60″S 156°39′40″E	2216	189.0	24.7	7.5	24.89	1.00	9.98	517
Reckling Peak [RKP]	76°15′29″S 158°36′35″E	1906	288.6	31.5	26.4	10.42	2.61	6.83	141
Elephant Moraine Main Icefield [EET1]	76°18′47″S 157°09′23″E	2001	74.4	31.3	18.5	10.42	2.61	111.68	354
Elephant Moraine Texas Bowl [EET2]	76°17′04″S 156°30′59″E	2035	295.9	32.8	19.6	10.42	2.61	44.08	1713
Elephant Moraine West [EET3]	76°02′12″S 155°39′41″E	2047	278.3	33.3	15.3	10.42	2.61	9.34	301
Frontier Mountain [FRO]	72°56′29″S 160°24′24″E	2141	86.4	16.0	65.5	3.56	3.96	86.30	798
Grove Mountains [GRV]	72°51′51″S 75°06′30″E	2021	454.3	96.8	68.3	8.17	2.50	37.64	3178
Sør Rondane Nansenisen Icefield [A]	72°48′35″S 24°24′05″E	2859	681.0	73.8	29.7	3.20	31.76*	138.78	2628

Note: Meteoritical Society Nomenclature Committee–approved abbreviated names for dense meteorite collection areas are noted in square brackets after each site name. Altitudes are areal means of the surface elevation within the meteorite stranding zone (MSZ) boundaries; ablation is calculated by use of Equation S5 in the Supplemental Material (see text footnote 1); SMB refers to the catchment surface mass balance and is taken from the RACMO (regional atmospheric climate model); and number of finds is taken from MetBull (2018). See the Supplemental Material, Section S1, for calculation of residency times and flux estimates, further details, and references.

*The mean velocity of the ice flow leaving the Sør Rondane Nansenisen Icefield is elevated due to the presence of a fast-moving ice stream in its vicinity. For the sake of consistency, Sør Rondane Nansenisen is treated in the same way as other connected ice flows and blue ice areas (see the Supplemental Material); if it were not, it would result in an ~4% reduction to the Antarctic find flux estimates. The ice flow velocity for other ice fields is in line with field measurements (~2 m yr^{-1}), though locally in stagnation points, it may be slower.

area of the ice sheet that feeds into it and then ablates. By assuming conservation of glacial mass (see the Supplemental Material[1]), we find the effective surface area to be 2.58× larger than the actual area, on average. This implies that the areas of the upstream catchments are significantly smaller than previously assumed (Sinisalo and Moore, 2010), but consistent with a recent study (Zekollari et al., 2019). In addition, by considering the ice surface velocity for each MSZ (see the Supplemental Material), we find that meteorites have a mean surface residency time scale of ~7.2 k.y. (neglecting the effect of wind, which removes lighter and smaller fragments much more quickly; Benoit and Sears, 1999; Folco et al., 2002). It is crucial to note that this surface residency time scale does not necessarily equate with a meteorite's terrestrial age (i.e., the duration of time since that meteorite arrived on Earth), which is likely to be far greater for englacial samples (Kehrl et al., 2018).

Then, considering the rate of accumulation and loss of meteorites on the MSZ, and incorporating individual meteorite collection masses for each MSZ (MetBull, 2018) (some 13,200 stones in total), we can infer the associated meteorite flux rate above a minimum sample mass (see the Supplemental Material). In so doing, we find that the central estimate for the flux of meteorites >50 g to Antarctica is 45.3 [32.3–63.4] km^{-2} $m.y.^{-1}$, where values in brackets denote the ±1 standard error.

Although meteorite fluxes are insightful, it is the fall flux (above a minimum total mass that reaches Earth's surface) that is more commonly used. To convert our Antarctic meteorite fluxes into fall fluxes, we must take account of meteorite pairing. Pairing the large number of Antarctic meteorites into individual falls is impractical (Zolensky, 1998). To make progress, we initially used pairing estimates from the literature, of between two and six meteorites per fall, inferred from a limited sample of meteorites (Zolensky et al., 2006). In this study, we focused on minimum terminal fall masses of 50 g, irrespective of the pairing factor. In so doing, we found the central estimate of the flux of Antarctic falls >50 g to lie between 17.6 km^{-2} $m.y.^{-1}$ (six meteorites per fall) and 32.2 km^{-2} $m.y.^{-1}$ (two meteorites per fall).

Before we can further improve upon the above Antarctic fall flux estimates and compare them to those of other geographically distinct studies, we must consider the effect of latitude. This dependency was hypothesized by Halliday (1964) but has not been verified observationally until now. By plotting the normalized frequency of satellite fireball observations (NASA CNEOS, 2018) against latitude (Fig. 2), we observe a clear latitudinal variation: the fireball frequency per unit area decreases as the latitude rises, to ~65% of the equatorial frequency at the poles. To model this latitudinal variation in fireball frequencies, we considered the trajectories of meteoroids emanating from the ecliptic plane under the influence of gravity, where daily and annual rotations of Earth cause longitudinal variations to average out (see the Supplemental Material; Halliday, 1964; Le Feuvre and Wieczorek, 2008).

The modeled fireball frequencies (solid line in Fig. 2) show a reasonable fit to the observations. Comparing our method to the assumption of a uniform model (see the Supplemental Material), we found that our latitudinal-variation model performs better than the uniform case (dashed line in Fig. 2) at the 95% confidence level ($p = 0.012$). Due to uncertainty in past satellite network coverage (Brown et al., 2002), we repeated this test on fireball data from the past 10 yr, and again found confidence at the 95% level. We also compared our result to an extant frequency-versus-latitude curve (Le Feuvre and Wieczorek, 2008) (dotted line in Fig. 2), calculated using a different methodology (aimed at improving impact-crater counting studies of solar system bodies). Again, we found that our latitudinal-variation model produces a better fit to the fireball data than the alternative at the 95% confidence level ($p = 0.033$).

Accounting for latitude variation is clearly essential for fairly comparing estimates from

[1]Supplemental Material. Ice flow model, pairing, calculation of total recoverable mass flux, latitudinal model, and fireball statistical analysis. Please visit https://doi.org/10.1130/GEOL.26213S.12101094 to access the supplemental material, and contact editing@geosociety.org with any questions.

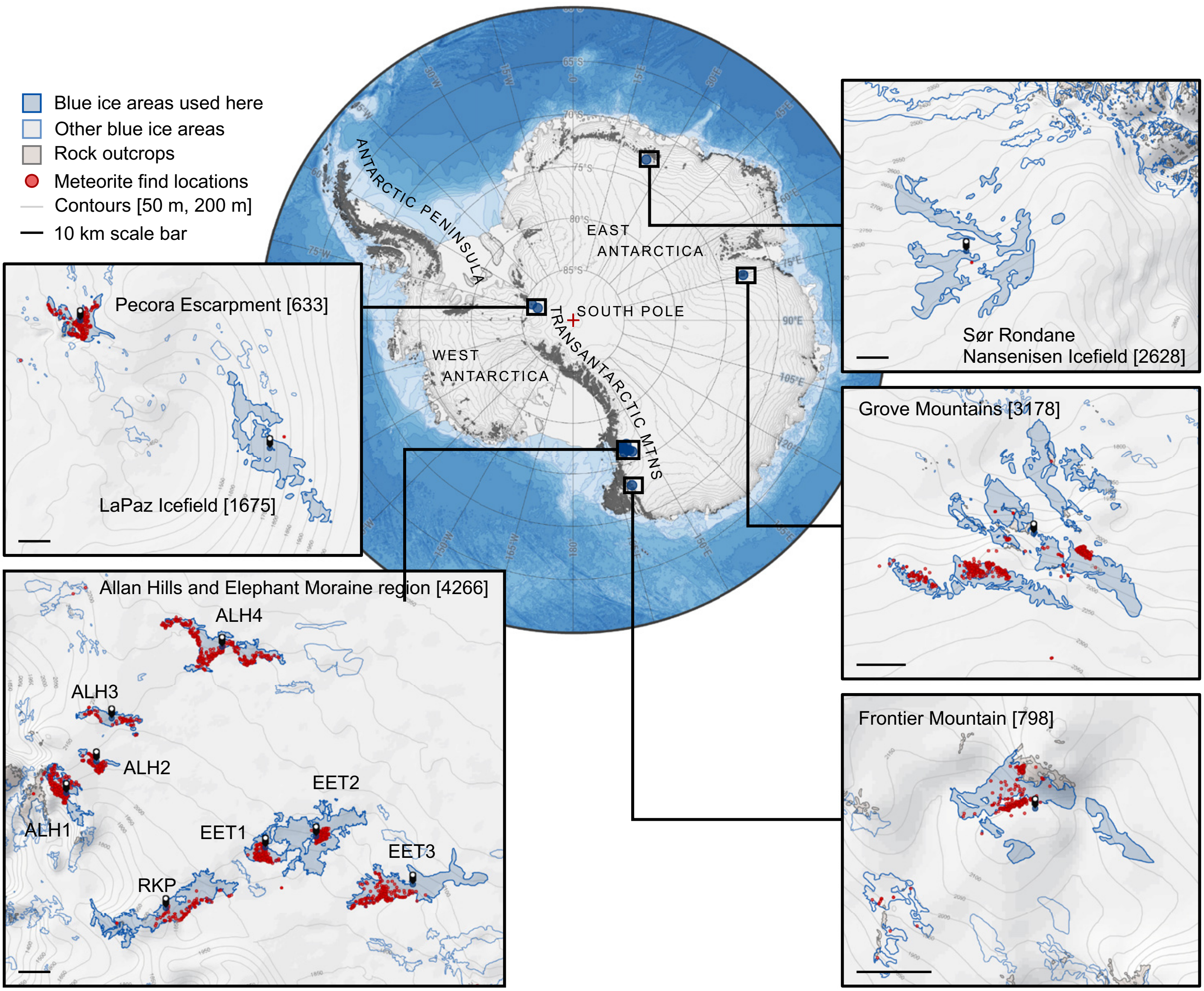

Figure 1. Map of Antarctica showing key meteorite stranding zones (MZSs) used in this study. Note that meteorites from some MSZs (LaPaz, Sør Rondane) have only nominal, and hence commonly identical, geographic coordinates entered in their Meteoritical Bulletin entry (MetBull, 2018). In such cases, only a single meteorite collection point appears. The total count of meteorites for each region is shown in square brackets after the area name. Orientations of inset maps are as shown on the central map (200 m contours are used on the central map, 50 m contours on the inset maps). Details of underlying geophysical data sets can be found in the Supplemental Material (see footnote 1). Icefields in the Allan Hills and Elephant Moraine region are as follows: ALH1—Allan Hills Main; ALH2—Allan Hills Near Western; ALH3—Allan Hills Mid Western; ALH4—Allan Hills Far Western; RKP—Reckling Peak; EET1—Elephant Moraine Main; EET2—Elephant Moraine Texas Bowl; EET3—Elephant Moraine West.

globally distinct meteorite accumulation zones. Using the result shown in Figure 2, it is now a simple matter to correct local flux estimates to their equatorial equivalents according to their latitude (see the Supplemental Material). This done, we calculated an effective pairing factor by carrying out a least-squares fit between our equatorial-equivalent fall fluxes and those obtained from previous studies (Bland et al., 1996; Halliday et al., 1996) over a minimum mass range of 10 g to 1 kg. A pairing factor of 3.18 minimized the residuals. This approach allowed us to circumvent the aforementioned issue of experimentally pairing the large number of Antarctic meteorites, and produces a metric that accounts for the sometimes subjective field-collection issue of whether or not two "nearby" samples should be considered part of the same fall. The Antarctic pairing factor is comfortably within the independently estimated range of 2 to 6, producing a local Antarctic fall flux >50 g of 25.8 km^{-2} m.y.$^{-1}$, while the equatorial-equivalent fall flux >50 g is 38.7 [26.8, 55.9] km^{-2} m.y.$^{-1}$. Likewise, the resulting fall flux fits comfortably within the equatorial-equivalent flux values from our key comparative studies (Bland et al., 1996 ; Halliday et al., 1996), which are 31.5 km^{-2} m.y.$^{-1}$ and 51.0 km^{-2} m.y.$^{-1}$, respectively. Although not directly comparable due to the 2 m.y. time period analyzed, Drouard et al. (2019)'s meteorite flux value >10 g of 234 ± 16 km^{-2} m.y.$^{-1}$ lies close to the upper standard error limit of our estimate (149 [101–219] km^{-2} m.y.$^{-1}$) when both are converted to equatorial equivalents, potentially due to wind effects.

Our equatorial-equivalent Antarctic-derived fall flux as a function of minimum mass is shown in Figure 3. The results show a well-established logarithmic decay in the number of falls with minimum mass (Huss, 1990), with a clear flattening below ~20 g (i.e., consistent with samples lost to wind removal; Schutt et al., 1986; Folco et al., 2002). Also plotted are the equator-equivalent fall fluxes from the literature (Bland et al., 1996; Halliday et al., 1996). It is evident

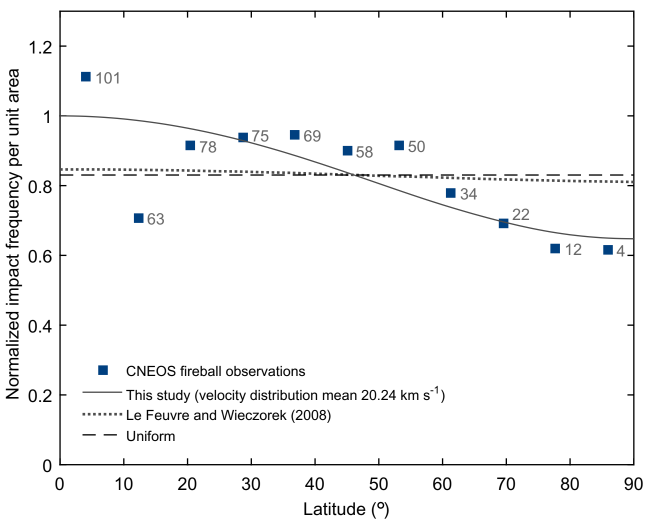

Figure 2. Latitudinal variation of Center for Near Earth Object Studies (CNEOS) binned (according to latitude band, as described in the Supplemental Material [see footnote 1]) fireball data (NASA CNEOS, 2018). Values next to each data point are the number of events contributing to that bin's frequency. All four data sets (CNEOS fireball observations, this study's model, Le Feuvre and Wieczorak's (2008) result, and the uniform assumption) are normalized and scaled such that modeled frequency (solid curve) takes the value of unity at the equator.

that all of these flux estimates are reassuringly close to one another. However, using a larger number of collection sites allows us to move beyond qualitative error estimates (Halliday et al., 1996) or simple ranges defined by two or three sites (Bland et al., 1996), and instead provide standard errors. Specifically, the best modern estimates were still subject to error factors of 2 to 3, while earlier studies differed by a factor of 7 (accumulation studies) or an order of magnitude or more (eyewitness falls) (Bland et al., 1996). Thus, ours appears to be a substantially more robust estimate than previous studies have been able to produce, particularly when weight is given to the fact that our estimates rely upon a much larger fraction of the global meteorite collection (22% and 13,200 samples versus ~250 events) (see the Supplemental Material).

Accounting for the latitudinal variation allowed us to expand our Antarctic results to a global setting. Using the best-fit pairing estimate, we determined a global expected fall flux of 17,600 [12,200–25,400] yr^{-1} for masses >50 g. Going further, we calculated the expected *recoverable* mass flux; that is, the mass flux derived by integrating the equatorial-equivalent Antarctic flux (Fig. 3) between the lowest observed collection mass and the highest expected collection mass during a systematic search (see the Supplemental Material; Huss, 1990). We estimate this equatorial-equivalent mass flux to be 36.6 [25.1, 53.4] kg km^{-2} m.y.$^{-1}$, a value which is 31% lower than an equatorial-equivalent estimate of 52.8 kg km^{-2} m.y.$^{-1}$ from the combined results of Halliday et al. (1996) and Bland et al. (1996). The corresponding total mass flux to Earth is 16,600 kg yr^{-1}. Interestingly, by focusing on the integrated mass flux between 10 g and 1 kg, we found equatorial-equivalent values to be 8.11 [5.69, 11.6] kg km^{-2} m.y.$^{-1}$, while the corresponding total mass flux to Earth is 3680 [2580, 5250] kg yr^{-1}—a value that is in agreement with previous estimates and yet better constrained (4380 kg yr^{-1}, Halliday et al., 1996; 2840–7150 kg yr^{-1}, Bland et al., 1996). This divergence at masses >1 kg may indicate a lower flux in the 1–100 kg range than previously modeled (Bland and Artemieva, 2006), or a limitation in determining mass flux of larger falls from Antarctic MSZs where the fall return period is greater than the residency time.

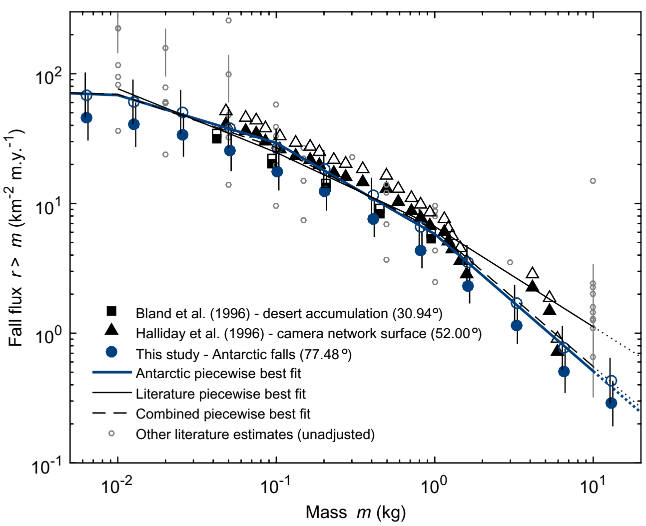

Figure 3. Meteorite fall flux (*r*) as a function of minimum mass (*m*). Solid symbols indicate local flux estimates; open symbols show their equatorial equivalents. Error bars representing the ±1 standard error range are offset for clarity. Also shown are best-fit lines to the Antarctic equatorial-equivalent data set, a data set based on two data sets from the literature (Bland et al., 1996; Halliday et al., 1996), and a combined data set calculated from all three (values in parentheses indicate mean latitude for each dataset). For masses where these are fit, they are shown as solid or dashed lines; where fits have been extrapolated to greater masses, dotted lines are used. Also shown are other estimates from the literature (see the Supplemental Material [see footnote 1]).

DISCUSSION

The emphasis in our work has been to use available glaciological and meteoritical data sets to calculate the extraterrestrial flux rate. However, the core relation (see the Supplemental Material, Equation S4) can be inverted to predict the expected meteorite number density of a potential MSZ when given the extraterrestrial flux rate. In fact, even without a flux rate estimate, a ranking of potential MSZ number densities can be obtained. Given the support required to operate remotely in Antarctica, to be able to predict new areas of the continent that are likely to hold significant accumulations of meteorites is extremely beneficial. Indeed this was the original purpose of our model. In planning the first United Kingdom–led Antarctica meteorite collection mission, we had predicted that an unvisited blue ice area near the Shackleton Range (East Antarctica) to have a meteorite number density of 10.8 [7.5, 15.6] km^{-2}. This mission to the Outer Recovery Ice Fields area was carried out during austral summer 2018–2019, finding a total (unclassified) meteorite number density of 7.1 km^{-2}, close to the lower 1 standard error estimate (Joy et al., 2019).

The latitude component of our modeling also has applications and implications beyond our immediate study. For example, it is possible to apply our latitude model to crater-counting studies on other planets. Yet at a societal level, it is the latitudinal variation of impact frequencies on Earth that likely carries the most importance—principally due to the independence of these results on meteorite mass. Consequently, our latitude model can be used as a likelihood weighting, which would help to geographically quantify threats and reassess flux estimates for large impactors, calculations that have predominantly been limited to analysis of the North American and European cratons. Finally, this work shows that equatorial regions face an appreciably greater risk of larger impactors—an increase of 12% relative to uniform latitudinal variation assumption—while at higher latitudes, the risk is reduced by 27%. As such, it may give additional reason for placing long-term contingency facilities at higher latitudes, such as the Global Seed Vault in Svalbard, Norway.

ACKNOWLEDGMENTS

This work was supported by The Leverhulme Trust (UK) grant RPG-2016–349; Royal Society (UK) grant

RS/UF140190; Science and Technology Facilities Council (STFC) grant ST/R000751/1; and Engineering and Physical Sciences Research Council (EPSRC) grant EP/R014604/1. We are grateful for useful discussions at the Royal Astronomical Society (UK) meeting held in November 2018 and at the European Geosciences Union General Assembly 2019. We are grateful to Vinciane Debaille and an anonymous reviewer for the time they have taken to review the manuscript and for their constructive suggestions. We also thank Benjamin Tipping and Philip Cartwright, who both assisted with preliminary work on the latitudinal aspect of this study.

REFERENCES CITED

Benoit, P.H., and Sears, D.W.G., 1999, Accumulation mechanisms and the weathering of Antarctic equilibrated ordinary chondrites: Journal of Geophysical Research, v. 104, p. 14,159–14,168, https://doi.org/10.1029/1999JE900015.

Bland, P.A., 2005, The impact rate on Earth: Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, v. 363, p. 2793–2810, https://doi.org/10.1098/rsta.2005.1674.

Bland, P.A., and Artemieva, N.A., 2006, The rate of small impacts on Earth: Meteoritics & Planetary Science, v. 41, p. 607–631, https://doi.org/10.1111/j.1945-5100.2006.tb00485.x.

Bland, P.A., Smith, T.B., Berry, F.J., and Pillinger, C.T., 1996, The flux of meteorites to the Earth over the last 50,000 years: Monthly Notices of the Royal Astronomical Society, v. 283, p. 551–565, https://doi.org/10.1093/mnras/283.2.551.

Bland, P.A., et al., 2012, The Australian Desert Fireball Network: A new era for planetary science: Australian Journal of Earth Sciences, v. 59, p. 177–187, https://doi.org/10.1080/08120099.2011.595428.

Brown, P., Spalding, R.E., ReVelle, D.O., Tagliaferri, E., and Worden, S.P., 2002, The flux of small near-Earth objects colliding with the Earth: Nature, v. 420, p. 294–296, https://doi.org/10.1038/nature01238.

Brown, P.G., et al., 2013, A 500-kiloton airburst over Chelyabinsk and an enhanced hazard from small impactors: Nature, v. 503, p. 238–241, https://doi.org/10.1038/nature12741.

DeMeo, F., 2017, Meteorites: A shift in shooting stars: Nature Astronomy, v. 1, 0041, https://doi.org/10.1038/s41550-017-0041.

Drouard, A., et al., 2019, The meteorite flux of the past 2 m.y. recorded in the Atacama Desert: Geology, v. 47, p. 673–676, https://doi.org/10.1130/G45831.1.

Evatt, G.W., Coughlan, M.J., Joy, K.H., Smedley, A.R.D., Connolly, P.J., and Abrahams, I.D., 2016, A potential hidden layer of meteorites below the ice surface of Antarctica: Nature Communications, v. 7, 10679, https://doi.org/10.1038/ncomms10679.

Folco, L., Capra, A., Chiappini, M., Frezzotti, M., Mellini, M., and Tabacco, I.E., 2002, The Frontier Mountain meteorite trap (Antarctica): Meteoritics & Planetary Science, v. 37, p. 209–228, https://doi.org/10.1111/j.1945-5100.2002.tb01105.x.

Gattacceca, J., et al., 2011, The densest meteorite collection area in hot deserts: The San Juan meteorite field (Atacama Desert, Chile): Meteoritics & Planetary Science, v. 46, p. 1276–1287, https://doi.org/10.1111/j.1945-5100.2011.01229.x.

Halliday, I., 1964, The variation in the frequency of meteorite impact with geographic latitude: Meteoritics, v. 2, p. 271–278, https://doi.org/10.1111/j.1945-5100.1964.tb01433.x.

Halliday, I., Griffin, A.A., and Blackwell, A.T., 1996, Detailed data for 259 fireballs from the Canadian camera network and inferences concerning the influx of large meteoroids: Meteoritics & Planetary Science, v. 31, p. 185–217, https://doi.org/10.1111/j.1945-5100.1996.tb02014.x.

Harvey, R.P., Schutt, J., and Karner, J., 2014, Fieldwork methods of the U.S. Antarctic Search for Meteorites program, *in* Righter, K., et al., eds., 35 Seasons of U.S. Antarctic Meteorites (1976–2010): A Pictorial Guide To The Collection: American Geophysical Union Special Publication 68, p. 23–41, https://doi.org/10.1002/9781118798478.ch2.

Heck, P.R., Schmitz, B., Bottke, W.F., Rout, S.S., Kita, N.T., Cronholm, A., Defouilloy, C., Dronov, A., and Terfelt, F., 2017, Rare meteorites common in the Ordovician period: Nature Astronomy, v. 1, 0035, https://doi.org/10.1038/s41550-016-0035.

Howie, R.M., Paxman, J., Bland, P.A., Towner, M.C., Cupak, M., Sansom, E.K., and Devillepoix, H.A.R., 2017, How to build a continental scale fireball camera network: Experimental Astronomy, v. 43, p. 237–266, https://doi.org/10.1007/s10686-017-9532-7.

Huss, G.R., 1990, Meteorite infall as a function of mass: Implications for the accumulation of meteorites on Antarctic ice: Meteoritics, v. 25, p. 41–56, https://doi.org/10.1111/j.1945-5100.1990.tb00969.x.

Hutzler, A., et al., 2016, Description of a very dense meteorite collection area in western Atacama: Insight into the long-term composition of the meteorite flux to Earth: Meteoritics & Planetary Science, v. 51, p. 468–482, https://doi.org/10.1111/maps.12607.

Joy, K.H., Crawford, I.A., Curran, N.M., Zolensky, M., Fagan, A.F., and Kring, D.A., 2016, The Moon: An archive of small body migration in the Solar System: Earth, Moon, and Planets, v. 118, p. 133–158, https://doi.org/10.1007/s11038-016-9495-0.

Joy, K.H., et al., 2019, The Lost Meteorites of Antarctica Project: A new UK-led Antarctic meteorite recovery programme: 50th Lunar and Planetary Science Conference 2019, abstract 1018.

Kehrl, L., Conway, H., Holschuh, N., Campbell, S., Kurbatov, A.V., and Spaulding, N.E., 2018, Evaluating the duration and continuity of potential climate records from the Allan Hills blue ice area, East Antarctica: Geophysical Research Letters, v. 45, p. 4096–4104, https://doi.org/10.1029/2018GL077511.

Le Feuvre, M., and Wieczorek, M.A., 2008, Nonuniform cratering of the terrestrial planets: Icarus, v. 197, p. 291–306, https://doi.org/10.1016/j.icarus.2008.04.011.

MetBull (Meteoritical Bulletin), 2018, Meteoritical Bulletin Database: https://www.lpi.usra.edu/meteor/metbull.php (accessed November 2018).

Miao, B., Xia, Z., Zhang, C., Ou, R., and Sun, Y., 2018, Progress of Antarctic meteorite survey and research in China: Advances in Polar Science, v. 29, p. 61–78, https://doi.org/10.13679/j.advps.2018.2.00061.

NASA CNEOS (National Aeronautics and Space Administration, Center for Near Earth Object Studies), 2018, NASA CNEOS Fireball Database: https://cneos.jpl.nasa.gov/fireballs/ (accessed June 2018).

Righter, K., Corrigan, C.M., McCoy, T.J., and Harvey, R.P., eds., 2014, 35 Seasons of U.S. Antarctic Meteorites (1976–2010): A Pictorial Guide To The Collection: American Geophysical Union Special Publication 68, 195 p., https://doi.org/10.1002/9781118798478.

Schmitz, B., Yin, Q.-Z., Sanborn, M.E., Tassinari, M., Caplan, C.E., and Huss, G.R., 2016, A new type of solar-system material recovered from Ordovician marine limestone: Nature Communications, v. 7, 11851, https://doi.org/10.1038/ncomms11851.

Schutt, J., Schultz, L., Zinner, E., and Zolensky, M., 1986, Search for meteorites in the Allan Hills region, 1985–1986: Antarctic Journal of the United States, v. 21, p. 82–83.

Sinisalo, A., and Moore, J.C., 2010, Antarctic blue ice areas—Towards extracting palaeoclimate information: Antarctic Science, v. 22, p. 99–115, https://doi.org/10.1017/S0954102009990691.

Zekollari, H., et al., 2019, Unravelling the high-altitude Nansen blue ice field meteorite trap (East Antarctica) and implications for regional palaeo-conditions: Geochimica et Cosmochimica Acta, v. 248, p. 289–310, https://doi.org/10.1016/j.gca.2018.12.035.

Zolensky, M., 1998, The flux of meteorites to Antarctica, ***in*** Grady, M.M., et al., eds., Meteorites: Flux with Time and Impact Effects: Geological Society [London] Special Publication 140, p. 93–104, https://doi.org/10.1144/GSL.SP.1998.140.01.09.

Zolensky, M., Bland, P., Brown, P., and Halliday, I., 2006, Flux of extraterrestrial materials, *in* Lauretta, D.S., and McSween, H.Y., eds., Meteorites and the Early Solar System II: Tucson, University of Arizona Press, p. 869–888.

Printed in USA