

Meteoric beryllium-10 fluxes from soil inventory measurements in the East River watershed, Colorado, USA

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Abstract. Meteoric beryllium-10 ($^{10}\text{Be}_{\text{met}}$) has a wide range of applications as a geochronometer and tracer of geological processes. $^{10}\text{Be}_{\text{met}}$ is produced in the atmosphere by cosmic rays and delivered to Earth's surface primarily via precipitation. $^{10}\text{Be}_{\text{met}}$ is particularly suitable for quantifying surface process rates where use of in situ-produced ^{10}Be is challenging, such as landscapes with quartz-poor bedrock. However, using $^{10}\text{Be}_{\text{met}}$ for dating and quantifying surface process rates requires constraining depositional fluxes across space and time. Although empirical and physical models for predicting fluxes exist, the predictions can deviate substantially from measured values. Here we quantify $^{10}\text{Be}_{\text{met}}$ flux in the East River watershed in Colorado, USA where precipitation is dominated by snowfall. We measured the $^{10}\text{Be}_{\text{met}}$ inventory in soils on five glacial moraines 13–18 ka in age that span 700 m of elevation and calculated $^{10}\text{Be}_{\text{met}}$ fluxes by dividing each inventory by moraine age. Inheritance-corrected fluxes range from 4.31×10^5 – 1.80×10^6 atoms $\text{cm}^{-2} \text{yr}^{-1}$ and fluxes corrected using modeled erosional and desorption losses are higher by up to a factor of 3.1 (TS1). The predicted fluxes are well correlated with elevation, mean annual precipitation, mean snow depth, and snow water equivalent ($R^2 = 0.71$ to 0.99). Regression models applied to gridded elevation, precipitation, snow depth, and snow water equivalent data predict watershed-averaged fluxes of 1.1×10^6 – 3.8×10^6 atoms $\text{cm}^{-2} \text{yr}^{-1}$. Predicted fluxes from a published empirical model that estimates fluxes as a function of precipitation were 1.8–3.8 times higher than inheritance-corrected site fluxes, but only 0.7–1.8 (TS2) times higher than erosion- and desorption-corrected fluxes calculated using a profile-average desorption model. Fluxes predicted by general cir-

culational models generally fall within the range of our empirically estimated watershed-averaged fluxes, although the degree of agreement depends on the predictor variable and whether inheritance-corrected or erosion- and desorption-corrected fluxes are used. Our results highlight both the importance of factors that drive variability in $^{10}\text{Be}_{\text{met}}$ delivery to soils and how local calibration can improve estimates of $^{10}\text{Be}_{\text{met}}$ flux in mountain watersheds.

1 Introduction

The cosmogenic nuclide beryllium-10 (^{10}Be) is used widely for geochronology and to quantify rates of Earth surface processes (Brown, 1984; Bierman and Nichols, 2004; Willenbring and von Blanckenburg, 2010; Granger et al., 2013). ^{10}Be forms during high energy collisions between cosmic particles and target nuclei (Lal and Peters, 1967). ^{10}Be produced in Earth's atmosphere (typically from N and O) is known as atmospheric, garden variety, or meteoric ^{10}Be ($^{10}\text{Be}_{\text{met}}$), whereas in situ-produced ^{10}Be ($^{10}\text{Be}_{\text{in situ}}$) is formed in mineral lattices at and near Earth's surface. Production rates of $^{10}\text{Be}_{\text{in situ}}$ are on the order of a few to tens of atoms $\text{g}^{-1} \text{yr}^{-1}$ in quartz (Gosse and Phillips, 2001; Borchers et al., 2016). In contrast, $^{10}\text{Be}_{\text{met}}$ is generated at orders of magnitude higher rates, with a global-averaged flux in excess of 1 million atoms $\text{cm}^{-2} \text{yr}^{-1}$ (Monaghan et al., 1986; McHargue and Damon, 1991). Prior to its deposition on Earth's surface by precipitation or dry fallout, $^{10}\text{Be}_{\text{met}}$ resides in the stratosphere and troposphere for 2 years and 55 d (TS3), respectively (Yamagata et al., 2019). Hence global

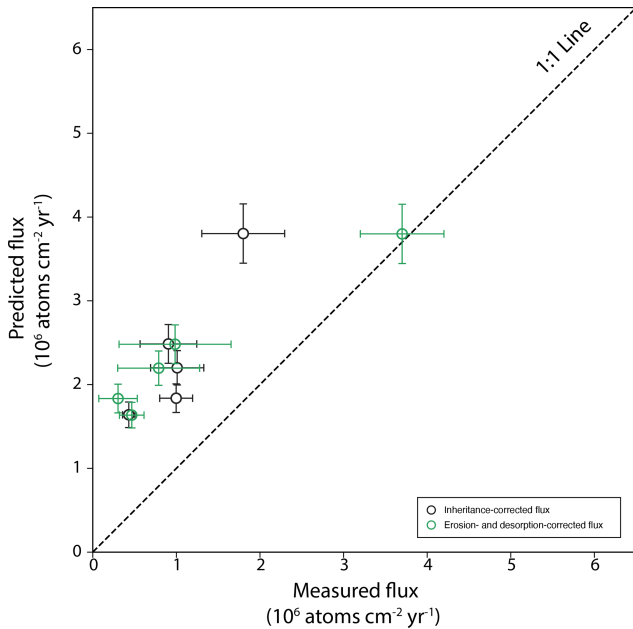


Figure 6. Predicted $^{10}\text{Be}_{\text{met}}$ flux from the empirical precipitation-based model of Graly et al. (2011), scaled to reflect Holocene-average values (e.g., Clow et al., 2020) versus measured flux values for the five study sites. Measured erosion- and desorption-corrected fluxes use the profile-average desorption model.

GCM-based predictions (Fig. 7). Hence, the GCM-based predictions generally fall within the range of our empirically estimated watershed-averaged flux values, although the degree of agreement depends on the predictor variable and whether or not fluxes are corrected for erosion and desorption.

Soils contain $^{10}\text{Be}_{\text{met}}$ scavenged from the atmosphere by aerosols, but also from dust particles that are derived from aeolian erosion and transported in the atmosphere before being deposited (Monaghan et al., 1986; Graly et al., 2011). The dust-derived or “recycled” $^{10}\text{Be}_{\text{met}}$ can be as much as $\sim 20\%$ of the total flux (Monaghan et al., 1986; Graham et al., 2003). Although the dust contribution to flux estimates does not need to be independently known to quantify surface process rates, provided that time-averaged delivery of dust to soils is representative of the timescale relevant to the surface process rate under investigation, dust contributions should be accounted for before comparing measured fluxes against predictions from GCMs. Hence the comparison of measured $^{10}\text{Be}_{\text{met}}$ fluxes against the GCM-based predictions is somewhat complicated by the likely contribution of dust to our measured values. The contribution of dust to $^{10}\text{Be}_{\text{met}}$ inventories in the East River is unconstrained (TS4), but dust fluxes inferred from lacustrine sediment in the nearby San Juan Mountains increased from ~ 0.01 to $0.4\text{ g cm}^{-2}\text{ yr}^{-1}$ over the last several centuries (Ballantyne et al., 2011) and recent snowpack measurements indicate seasonal dust fluxes are on the order of $5\text{--}10\text{ g cm}^{-2}\text{ yr}^{-1}$ (Lawrence et al., 2010). Dust

fluxes in the Colorado Front Range are $0.1\text{--}0.2\text{ g cm}^{-2}\text{ kyr}^{-1}$ (Dethier et al., 2012). Dust fluxes in the Front Range contribute $< 10\%$ to the total flux of $^{10}\text{Be}_{\text{met}}$ (Ouimet et al., 2015). If the contribution of dust in the East River is comparable to that in the Front Range, accounting for dust would not substantially influence the magnitude of discrepancies between GCM-based predictions and our empirically derived $^{10}\text{Be}_{\text{met}}$ flux estimates.

At a regional level, $^{10}\text{Be}_{\text{met}}$ fluxes for the Colorado Front Range based on soil inventories have been estimated to be $1.5 \pm 0.2 \times 10^6\text{ atoms cm}^{-2}\text{ yr}^{-1}$ (Ouimet et al., 2015). Soil inventory-based $^{10}\text{Be}_{\text{met}}$ fluxes in the Wind River Mountains, Wyoming are $1.46 \pm 0.20 \times 10^6$ and $1.30 \pm 0.48 \times 10^6\text{ atoms cm}^{-2}\text{ yr}^{-1}$ for Pinedale- and Bull Lake-aged moraines, respectively (Clow et al., 2020). The $0.43\text{--}1.8 \times 10^6\text{ atoms cm}^{-2}\text{ yr}^{-1}$ F_{met} values and $0.31\text{--}3.70 \times 10^6\text{ atoms cm}^{-2}\text{ yr}^{-1}$ F_{cor} values we measure are consistent with those from the Front Range and Wind River Mountains, though those sites are drier, with $\sim 500\text{ mm yr}^{-1}$ of mean annual precipitation in the Front Range (Ouimet et al., 2015) and 276 mm yr^{-1} at the Wind River Mountains sites (Clow et al., 2020), relative to the 585 to 1353 mm yr^{-1} precipitation at the five East River study sites. The driest site in the East River (terminal moraine, 585 mm yr^{-1} MAP) has F_{met} and F_{cor} values of 0.43×10^6 and $0.47 \times 10^6\text{ atoms cm}^{-2}\text{ yr}^{-1}$, respectively, which are lower than fluxes inferred in the Front Range and Wind River Mountains. These comparisons suggest that precipitation contributes to regional differences in $^{10}\text{Be}_{\text{met}}$ flux, but does not explain all of the variability among sites.

Local calibration of $^{10}\text{Be}_{\text{met}}$ flux greatly increases the utility of $^{10}\text{Be}_{\text{met}}$ as a tracer of surface processes in the East River watershed, where there is prevalent shale bedrock that is not very amenable to the more common $^{10}\text{Be}_{\text{in situ}}$ method. Our findings show that, whereas $^{10}\text{Be}_{\text{met}}$ flux predictions from GCM-based models are broadly applicable for large-scale watershed applications, such models do not capture the high spatial variability in $^{10}\text{Be}_{\text{met}}$ fluxes that is driven by orographic influences on precipitation. Hence using $^{10}\text{Be}_{\text{met}}$ to quantify physical erosion and weathering rates at the small watershed or soil profile-scale requires not only local-scale calibration of $^{10}\text{Be}_{\text{met}}$ fluxes, but also a means for predicting $^{10}\text{Be}_{\text{met}}$ fluxes for sites where elevation and precipitation are different from that of the sites used for calibration. Our study demonstrates how high-resolution LiDAR elevation and snowpack datasets can be combined with locally calibrated $^{10}\text{Be}_{\text{met}}$ flux measurements to generate spatially resolved flux predictions, which furthers our understanding of the processes that control the delivery of $^{10}\text{Be}_{\text{met}}$ to soils.

6 Conclusions

Meteoric ^{10}Be fluxes calculated from soil inventories on five glacial moraines dated to $13.0\text{--}17.9\text{ ka}$ in the East