Atmospheric dust affects Earth’s radiative balance and is climatically important. Dust is argued to have played an important role in past natural climate changes through glacial cycles, yet temporal and spatial variability remain poorly constrained and calculations of the radiative impact of dust over such timescales often assume that a distal record from Antarctica represents global dust variations. Environmental magnetism can provide powerful parameters for determining hematite contents in dust from hyper-arid deserts and can therefore make important contributions to understanding the global dust cycle. We present a high-resolution dust record from the Red Sea (with dust sourced mainly from Arabia) with a precise chronology relative to global sea level/ice volume variability. Our record correlates well with a high-resolution Asian dust record from the Chinese Loess Plateau (CLP). Chinese loess chronology is notoriously problematical on millennial timescales. Correlation between these records enables importation of our Red Sea chronology to the CLP, which provides the first precise timescale for the CLP for the last 500,000 years. Dust fluxes in these two major global dust source regions are high even through interglacials, with strong superimposed millennial-scale variability. Conversely, the distal Antarctic record is biased to sharply delineated glacial/interglacial contrasts. Models based on Antarctic dust records will therefore overestimate the radiative contrast of atmospheric dust loadings on those timescales. Additional differences between Arabian/Asian, circum-Saharan and Antarctic dust records reveal that climate models could be improved by avoiding ‘global mean’ dust considerations and instead including large-scale regions with different dust source variability.