Geophysical Research Abstracts
Vol. 18, EGU2016-13959, 2016
EGU General Assembly 2016

Quantifying atmospheric processing of mineral dust as a source of bioavailable phosphorus to the open oceans

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The transport and deposition of mineral dust is known to be the dominant source of phosphorus (P) to the surface waters of the open oceans. However, the fraction of this P that is deemed available for primary productivity remains a key uncertainty due to a limited understanding of the processes occurring during transport of the dust. Through a series of detailed laboratory experiments using desert dust and dust precursors, we show that the dissolution behaviour of P in these samples is controlled by a surface-bound labile pool, and an additional mineral pool primarily consisting of apatite. The acid dissolution of the apatite occurs rapidly and is controlled by the absolute number of H+ ions present in the solution surrounding the dust. Using these results we develop a new conceptual model that reproduces the major processes controlling P dissolution in the atmosphere. We then use a global aerosol microphysics model with a global soil database to quantify the deposition of bioavailable P to the open oceans and ice sheets. We show that, globally, the labile pool contributes 2.4 Gg P a^{-1} to the oceans and, from a potential pool of 11.5 Gg P a^{-1}, the dissolved apatite pool contributes 0.24 Gg P a^{-1}. A series of sensitivity studies identifying sources of acid in the atmosphere show that anthropogenic emissions of SO_2 contribute 61% of the global mass of dissolved apatite, volcanic events contribute 11%, and DMS emissions contribute 10%. Finally, we show that the fraction of mineral dust P that is available for primary productivity varies, regionally, from $<$20% in the North Atlantic Ocean to $>$50% in the South Pacific Ocean; this explains the variability in the fraction of bioavailable P commonly observed in important oceanic regions.