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Quantifying Mineral Dust Mass Budgets: Terminology, Constraints, and Current Estimates

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Mineral dust aerosol is created by wind erosion of soil particles. In addition to its direct radiative effect, dust aerosol mediates ocean carbon uptake and the chemical cycles of other aerosols like sulfates. Dust observations during the past decade span measurements of local concentration and deposition to global satellite retrievals of aerosol optical thickness [*Prospero et al.*, 2002].

Measurements of dust emission, whereby soil particles enter the atmosphere, are scarce. Because no single data set is sufficient to constrain the three-dimensional distribution of dust aerosol and its evolution with time, the dust cycle is currently estimated using models that are constrained by available measurements and retrievals.

However, a survey of recent models (Table 1) shows that estimates of emission range over more than a factor of 2. This translates into a corresponding uncertainty in the climate effect of dust.

One goal of this article is to draw awareness to the wide range of model estimates of dust emission and atmospheric loading. Comparison is made difficult by the different assumptions made by modelers. For example, some models include dust sources created by human disturbance of the soil (by agriculture or overgrazing, for example), while others include only natural sources.

Participants at the Second International Workshop on Mineral Dust, convened in Paris, 10–12 September 2003, agreed that the binary division of dust into "natural" and "anthropogenic" emissions is inadequate, and that scientific progress, and the policy which it informs, requires more precise nomenclature. While natural dust sources like deserts are easily visualized, anthropogenic dust sources come in many forms. A consensus terminology is necessary to objectively define, attribute, and intercompare dust mass (and number) budgets and forcings.

The second goal of this article is to propose a terminology distinguishing different anthropogenic contributions to the dust cycle that is useful for both scientists and policy makers. Distinguishing dust that results from anthropogenic land use change (and is potentially remediable) from dust arising from anthropogenic climate change has important consequences for environmental planning. Though dust from all sources combines in the real atmosphere, making provenance difficult to discriminate in observations, it can be distinguished in models. This proposed taxonomy attempts to provide a basis for comparison between models.

Current Estimates and Constraints

The size range of particles represented by each model is crucial for comparing emission estimates. If counted, short-lived large particles dominate mass emission budgets. For intercomparison purposes, models and measurements should provide emission (and deposition) estimates in a standard size range. Diameter $D < 10$ μm is recommended. This includes a majority of the far-traveled particles that are distributed globally, and meshes with the Particulate Matter < 10 μm (PM10) air quality measurement and regulation standard.

Since 2001, published dust emission estimates for the present climate range from 1000–2150 Tg yr^{-1} (Table 1). Atmospheric burden estimates range from 8–36 Tg, an uncertainty factor that exceeds 4. Uncertainty regarding deposition processes which control dust lifetime compound emissions uncertainties to create this surprisingly large discrepancy. It remains unknown how much uncertainty results from insufficient observational constraints and how much arises from different representations among the models of mobilization, transport, and deposition processes [*Luo et al.*, 2003; *Zender et al.*, 2003]. This emphasizes the importance of incorporating observations of dust burden (or proxies such as optical depth) into model estimates (e.g., through assimilation). Few studies provide quantitative estimates of uncertainties such as natural variability and model error. Including these would more completely represent, and further widen, the estimated range of mass budgets.

In situ observations provide many promising, though underutilized, mass constraints. *Zender et al.* [2003] selected the best estimate among four different emissions models by minimizing biases against observations of concentration, distribution, and spatial correlation. Further constraints to the minimization problem include the Aerosol Robotic Network (AERONET) data, sediment data, and chemical data. Incorporation of observational constraints (e.g., through assimilation or error minimization techniques) helps reduce propagation of model and meteorology uncertainties into mass budget estimates. Making observations available in self-describing software formats with consistent spatial and temporal grids would facilitate this.

Satellite observations are more suited to constrain burden than emissions on a global scale. The global dust aerosol burden is nearly proportional to its optical depth, assuming most atmospheric dust mass is carried as optically efficient clay-size particles. Global dust optical depth is now available through satellite retrieval algorithms for incorporation into aerosol assimilation schemes. Such schemes in theory provide better global mass constraints than in situ emission or deposition measurements, which are too few for adequate global coverage. Although the retrieved optical thickness summed over all aerosol species remains uncertain to within a factor of 2 [*Myhre et al.*, 2004], this is still smaller than the range of dust loading estimated by models.

Large-scale transport models have trouble reproducing the transport of large dust particles measured in remote stations. The Puerto Rico Dust Experiment (PRIDE) campaign (2000) intercompared several size distribution measurement techniques. Dust mass median diameter (MMD) in Barbados was 3.5 ± 1 μm based on aerodynamic methods and 9 ± 1 μm based on optical methods. During the Intercontinental Transport and Chemical Transformation Field Mission in the spring of 2002, the MMD of springtime East Asian dust reaching the west coast of North America was greater than 5 μm (K. Perry, personal communication, 2003). Dust MMD in most models is about 2.5 μm.

The twofold discrepancy between modeled and measured MMD of long range dust implies that model mass budgets may be systematically biased. This bias manifests as an underestimate of large particle mass and an overestimate of small particle mass. Note that this bias might not be apparent from retrievals of optical depth that are more sensitive to the smaller particles.

Proposed Source Classification

Models simulate natural and various anthropogenic categories of dust that are difficult or impossible to discriminate in observations. The relative importance of these categories varies regionally and temporally. The aerosol modeling community must first objectively identify and distinguish all useful categories of dust emissions, i.e., "natural," "anthropogenic," and so forth. A more precise taxonomy will facilitate model intercomparison.

Natural Dust. Natural dust is rather intuitive. It is mobilized by wind stress or other natural mechanisms (thermophoresis, electrostatics) over undisturbed source regions. Regions that emitted dust (perhaps intermittently) in the preindustrial era are considered natural sources, although some additional sources have been created since then by nonanthropogenic climate shifts, due to solar forcing or natural variability, for example. The baseline period used to define natural sources should be explicitly specified, since desert aerosol emissions vary dramatically through the paleoclimate record. It is recommended to reference present climate natural sources to a baseline period ending circa 1750 when CO_2 concentration was about 280 ppm.

Anthropogenic Dust. Anthropogenic dust refers to dust activity (emission and suppression) that is present due to human activity. Humans can influence dust emissions in two ways: (1) by land use which changes soil surface conditions, and (2) by modifying the climate, which in turn modifies dust emissions.

Anthropogenic Dust of the First Kind. This category consists of dust production and emission changes due to human activities that directly modify or disturb the land surface

and thereby alter soil erodibility. Agriculture, construction, mining, livestock, vehicles, and war do this in two stages. First, the soil disturber (e.g., tire, hoof, plow) may mechanically inject some dust into the atmosphere, independent of wind speed. Second, the mechanical disturbance weakens soil cohesion and ruptures soil crusts, leaving the surface more erodible. Subsequent anthropogenic dust production occurs as wind erosion deflates the disturbed surface.

Anthropogenic dust of the first kind must account for direct dust injection as well as wind erosion changes due to soil erodibility modification from current, recent, and far past human activities. The classic examples of anthropogenic dust regions of the first kind are the Aral Sea and Owens Lake, whose beds were exposed by water diversion projects. Another example is the 1930s Great Plains Dust Bowl.

Dust suppression mechanisms corresponding to anthropogenic sinks of the first kind include short-term strategies such as soil wetting, irrigation, and short-duration artificial surface cover. Strategies that reduce emissions over longer periods include planted or constructed windbreaks, vegetative ground cover, and artificial wetlands.

Users and consumers of dust statistics may wish to further subdivide this category. For example, decision makers could benefit from knowing which sources are manageable through short-timescale policy enforcement. To accommodate this need, modelers and observers might distinguish anthropogenic emissions expected to cease shortly after the anthropogenic activity ceases ("short-term" or "active" dust sources such as plowing) from dust from regions activated by previous land use that are not significantly disturbed by ongoing activities ("long-term" or "passive" dust sources such as the exposed Aral Sea bed). For agricultural disturbance cycles, the natural timescale to divide short-term from long-term dust sources would be 1 year.

Anthropogenic Dust of the Second Kind. This category represents changes in emissions and deposition due to all anthropogenic effects on climate. Effects which alter deposition include changes in cloud structure, precipitation, and solubility effects of anthropogenic aerosols such as sulfate. The antecedent human activities responsible include greenhouse gas emissions, aerosol emissions, and land-use change. These forcings change wind, precipitation, leaf area, radiation, and soil moisture patterns, which may be diagnosed as separate feedbacks in models.

Vegetation change contributes to both kinds of anthropogenic dust. Agriculture directly modifies soil erodibility and plant cover, and thus contributes to dust of the first kind. Changes in vegetation due to plant physiological response to altered CO_2 and climate contribute to anthropogenic dust of the second kind.

Identification of dust of the second kind is difficult because attribution of regional anthropogenic climate change is fraught with uncertainty. For example, the Aral Sea region may be experiencing lower than historical precipitation due to natural variability or due to a strong soil albedo feedback from lower lake levels. Which hypothesis is correct helps determine whether a change in water policy is appropriate or else irrelevant for dust remediation.

Table 1. Present Climate Dust Budget Estimates.

Reference	*Emissions E Tg yr^{-1}*	*Time τ Days*	*Burden M Tg*
Duce et al. [1991]	(910)		
Tegen and Fung [1994]	3000		
Tegen and Fung [1995]	1222		
Andreae [1996]	1500	5.6	18.8
Prospero [1996]	(358)	4	8.4
Mahowald et al. [1999]	3000		
Penner et al. [2001]	2150		
Ginoux et al. [2001]	(478)\1814		
Chin et al. [2002]	1650	7.1	35.9
Werner et al. [2002]	1060 ± 194	6.3	28.7
Tegen et al. [2002]	1100	2.8 ± 0.5	8 ± 3
Zender et al. [2003]	(314)1490 ±160	7.4	22.2
Luo et al. [2003]	1654	4.3 ± 1.0	17.4 ± 2
Mahowald and Luo [2003]	1654	5.1	23
Miller et al. [2004]	1018	5.1	23
Tegen et al. [2004]	1921	5.2	14.6

Shown are annual emissions E [Tg yr^{-1}], atmospheric turnover time τ [d], and atmospheric burden M [Tg]. Estimates of deposition to oceans are parenthesized. Order is chronological. The Eos *Electronic supplement contains full citation information.*

Recommendations for Future Research

Because dust may change climate and feed back upon dust emission, these categories are not completely independent. For example, radiative forcing by dust from anthropogenic sources alters the circulation, which feeds back upon dust emission from natural sources. *Perlwitz et al.* [2001] estimate that this feedback changes the global dust load by roughly 15%, so that disentangling these second-order effects is probably of little practical importance.

Recent studies show a fourfold difference in total dust mass burden estimates, twice as great as the difference in emission estimates. This range would increase if researchers published the uncertainty that arises from input field uncertainty and discretization. *Luo et al.* [2003] showed that different analyzed meteorology data sets (NCEP and DAO) produce, in the same transport model, total dust estimates which differ by more than the total estimated anthropogenic dust mass.

Modeling and observation strategies to enhance the signal of anthropogenic dust amid the noise of natural variability and model error will be critical to future studies. Few dust mass budget estimates in the literature distinguish between natural and anthropogenic dust, much less between the two anthropogenic categories we propose. It is recommended that future studies attempt to distinguish these categories and any subcategories especially useful to decision makers. This requires an interdisciplinary community effort to identify and distinguish useful source types.

The *Eos* Electronic Supplement of this Feature can be found at http://www.agu.org/eos_elec/000790e.html.

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