Relative importance of climate and land use in determining present and future global soil dust emission

I. Tegen, M. Werner, S. P. Harrison, and K. E. Kohfeld

Max Planck Institute for Biogeochemistry, Jena, Germany

Received 4 December 2003; revised 22 January 2004; accepted 2 February 2004; published 3 March 2004.

[1] The current consensus is that up to half of the modern atmospheric dust load originates from anthropogenically-disturbed soils. Here, we estimate the contribution to the atmospheric dust load from agricultural areas by calibrating a dust-source model with emission indices derived from dust-storm observations. Our results indicate that dust from agricultural areas contributes <10% to the global dust load. Analyses of future changes in dust emissions under several climate and land-use scenarios suggest dust emissions may increase or decrease, but either way the effects of climate change will dominate dust emissions. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0322 Atmospheric Composition and Structure: Constituent sources and sinks; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions. **Citation:** Tegen, I., M. Werner, S. P. Harrison, and K. E. Kohfeld (2004), Relative importance of climate and land use in determining present and future global soil dust emission, *Geophys. Res. Lett.*, *31*, L05105, doi:10.1029/2003GL019216.

1. Introduction

[2] The magnitude of climate forcing by soil dust aerosol is uncertain but potentially important [*Houghton et al.*, 2001]. To understand historical and possible future changes in dust emissions, the percentage of atmospheric dust load originating from anthropogenic changes in land use must be quantified. It has been estimated that up to 50% of the modern dust originates from such sources, but these estimates are based on only two studies. One study estimated that disturbed areas comprised 20% of modern dust sources and assumed a comparable contribution to the atmospheric dust load [*Sokolik and Toon*, 1996], the other found a contribution of 30–50% from anthropogenically-disturbed soils needed to be added to modeled dust loads in order to match remotely sensed aerosol optical thickness [*Tegen and Fung*, 1995]. *Mahowald et al.* [2002] show that the assessment of the role of anthropogenic activity in the atmospheric dust cycle is limited by the accuracy of the available data sets. Recent satellite observations, however, suggest that dust emissions from agricultural areas are of minor importance [*Prospero et al.*, 2002]. Here we present a new estimate of contribution of dust emissions from agricultural sources according to *Tegen and Fung* [1995] the largest 'anthropogenic' dust source together with an estimate of possible future changes in dust emissions.

2. Dust Storm Frequency in Agricultural Areas

[3] In the absence of a global data set of dust emissions we quantify the effect of land use using dust storm frequencies (DSF) as an index for dust emissions, assuming that dust storms provide the largest source for aeolian dust. We compare DSFs in undisturbed and disturbed areas in the same bioclimate. The DSF data set from the International Station Meteorological Climate Summary (ISMCS) [*Engelstaedter et al.*, 2003] provides multi-decadal averages for 2249 stations of the number of days per year on which dust storms (events when visibility is <1 km because of dust) occurred. The DSF data have been screened for stations where observations were clearly influenced by transported dust. Although the data may have been affected by, e.g., observation errors or presence of local sources, *Engelstaedter et al.* [2003] still found close relationships between the observed DSFs and surface conditions in the dust source areas.

[4] The location of agricultural areas was derived from the 0.5° gridded data in [*Ramankutty and Foley*, 1999] (RF99) and [*Klein Goldewijk*, 2001] (KG01). KG01 distinguish rangeland, cropland and natural vegetation, using statistical information on national and sub-national level and population density. RF99 estimate the percentage of cultivation within each grid cell using remote sensing and statistical information. Here, we consider RF99 grid cells with <5% cultivation as equivalent to natural vegetation and distinguish cells with moderate (5–50%) and with high (>50%) levels of cultivation. This subdivision was chosen to optimize the statistical significance of the results.

[5] DSFs increase with decreasing vegetation cover, as measured by the mean fraction of absorbed photosynthetically active radiation (FPAR) derived from a 12-year average of the Normalized Difference Vegetation Index measured by AVHRR [*Knorr and Heimann*, 1995], and plant-available soil moisture, as measured by the ratio of actual to equilibrium evapotranspiration (α) (Figure 1). However, median and mean DSFs from agricultural sites are significantly higher than those from non-agricultural sites in non-forest regions (Figures 1a and 1c), except in the case of regions with very low vegetation cover (<10% FPAR). The difference between DSFs from agricultural and natural sites is less marked when the records are grouped by α, indicating that the differences within each vegetation-cover class reflect differences in vegetation cover caused by land use.

[6] To estimate the contribution of agricultural and non-disturbed areas to global dust emissions from the DSF results, we use a model that computes dust emissions (at 0.5° resolution) based on surface wind speed, soil moisture, vegetation and snow cover, and specifies topographic

0094-8276/04/2003GL019216$05.00

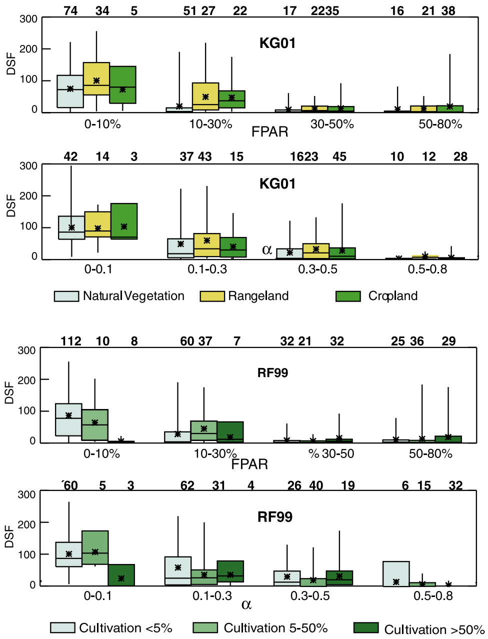

Figure 1. Dependence of DSF in non-forested areas on vegetation cover and plant available soil moisture in different land-use categories. Vegetation cover is indicated by FPAR, and soil moisture by α (see text). The top two panels show DSFs in natural vegetation, rangeland and cropland (KG01). The bottom two panels show DSFs in natural vegetation, intermediate-level cultivation and intensive cultivation (RF99). Median DSFs are marked by horizontal lines, the means by stars, and the box limits correspond to the 25th and 75th percentiles. The vertical line indicates the maximum range of the data.

depressions as favorable sources of dust [*Tegen et al.*, 2002]. Dust emissions were computed for 10 years (1983 to 1992), using meteorological fields (sampled at 6-hourly intervals) from the European Centre for Medium range Weather Forecast reanalysis. For comparison with the observations we defined a day in which dust emission occurred in the model as 'dust storm day' for the respective model gridcell. The dust emission model underestimates the number of days on which emissions occur in regions of natural vegetation by a factor of two (the slope is 0.56* observed DSF in KG01 natural vegetation and 0.53* observed DSF in RF99 areas with <5% cultivation; neither regression shows a significant offset from zero). This discrepancy arises because the temporal and spatial sampling scales of the model are coarser than those of the observations. We apply a global correction by lowering the wind stress threshold for dust emission by 0.86. This correction raised simulated DSFs to a comparable magnitude as observed DSFs in regions of natural non-forested vegetation (Table 1). Simulated DSFs are still smaller than observed DSFs from agricultural sites in non-forested regions (Table 1). In those grid cells we therefore further lowered the wind stress threshold required to initiate dust emission that matches the observed increase in DSFs for agricultural sites. The required additional wind stress correction factor is 0.93 for rangeland and 0.73 for cropland (KG01), and 0.86 for intermediate-level (5–50%) and 0.70 for intensive (>50%) cultivation (RF99). The global contribution of dust emission from agricultural soils, computed from the difference between the simulated emission fluxes for the baseline case (Figure 2a) and the lowered-threshold case (Figure 2b), is then 5% (RF99) or 7% (KG01). This is less than one fifth of the previous estimates of the anthropogenic contributions to the total dust load.

3. Future Projections of Dust Emissions

[7] Dust emissions from natural sources may change in future as a result of anthropogenically forced climate changes. Using a projection from the National Center for Atmospheric Research's coupled Climate System Model, *Mahowald et al.* [2003] suggest that global dust emissions may decrease by 20–60% by 2090, mainly as a consequence of a climate-induced decrease in desert extent. We used two projections of future climate based on the IPCC IS92a scenario [*Houghton et al.*, 2001] to estimate future dust emissions. We forced the dust model [*Tegen et al.*, 2002] with T106 meteorological fields based on the ECHAM4-OPYC model for the years 1970–1980 and 2040–2050 [*Roeckner et al.*, 1999], and with meteorological fields from the HADCM3 model for the years 1970–1980 and 2070–2080 [*Johns et al.*, 2003], both with 12-hourly time intervals. The computed modern annual dust emissions differ by ca. 20% for different wind fields. Daily changes in vegetation cover were computed based on the vegetation-phenology model BIOME4 [*Kaplan et al.*, 2003] forced by the simulated temperature, precipitation and surface radiation fields [*Werner et al.*, 2002]. Thus, the simulated changes in dust emissions reflect both changes in vegetation cover, including the effect of the enhanced

Table 1. Observed and Simulated (10-Year Averages, Model Results Without Increased Emissions in Agricultural Areas) Mean Dust Storm Frequencies (DSFs, Given in Days/Year)

		KG01			RF99		
		Uncultivated	Rangeland	Cropland	<5% cultivation	5–50% cultivation	>50% cultivation
Non-forest	Observed	15.7 (1.1–7.7)	26.1	23.5	18.9 (0.7–19.)	24.0	17.0
	Model (baseline)	15.7 (0–12.)	16.9	8.3	18.6 (0–9.8)	8.3	7.7
	Difference (observed excess)	0	9.2	15.2	0.3	15.7	9.3
Forest	Observed	3.4	3.8	3.8	3.6	4.3	2.8
	Model (baseline)	0.2	0.0	0.2	0.0	0.0	0.2
	Difference (observed excess)	3.2	3.8	3.6	3.6	4.3	2.6

The numbers in brackets are the 25th to 75th percentile range of the observations and model results. We distinguish between natural, rangeland and cropland areas as defined in KG01, and between low (<5%), intermediate (5–50%) and intense cultivation (>50%) in RF99. The results are averaged for grid cells which contain stations. Differences in bold indicate that modeled and observed mean values are significantly different at the 0.01 level for square-root transformed data.

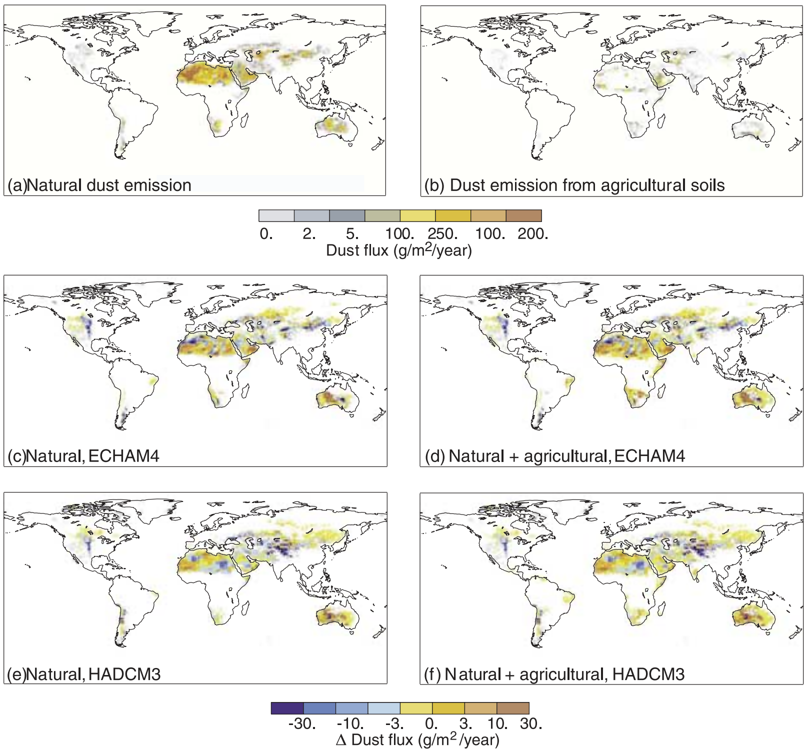

Figure 2. Modelled annual dust emissions. (a) Modern dust emission from natural soils; (b) dust emissions from cultivated soils, based on the KG01 distribution of rangeland and cropland; (c) difference between a scenario of future dust emissions for the years 2040–2050 and emissions for 1970–1980 for natural soils, computed with meteorological fields from ECHAM4 with IS92a IPCC scenario; and (d) as (c), but including increased dust emissions from cultivated soils, according to the IPCC A2 scenario; (e) difference between a scenario of future dust emissions for the years 2070–2080 and emissions for1970–1980 for natural soils, computed with meteorological fields from HADCM3 with IS92a IPCC scenario; and (f) as (e) but including increased dust emission from cultivated soils, according to the IPCC A2 scenario.

atmospheric CO_2 concentration on vegetation density, and changes in meteorological variables that directly influence dust emission.

[8] When taking only modern natural sources into account, projected dust emissions *increase* by 9% according to the ECHAM4-driven simulation (Figure 2c, Table 2), and *decrease* by 19% according to the HADCM3-driven (Figure 2e, Table 2) simulation. Both simulations show increased dust emissions in Australia, northern Africa and Asia north of 55°N, and decreased emissions from North America and central Asia. The ECHAM4 climatology produces a 26% reduction in dust emissions from eastern Asia (35–50°N, 85–130°E), while the HADCM3 climatology produces a 19% reduction, reflecting a much smaller increase in vegetation cover. In the central and eastern Sahara, dust emissions *increase* by 11% in the ECHAM4-driven simulation, while *decreasing* by 4% in the HADCM3-driven simulation. While the increase in the ECHAM4-driven simulation is caused by higher surface wind speeds, the decrease in the HADCM3-driven simulation reflects the significantly increased vegetation cover caused by increased monsoon precipitation.

[9] In additional simulations in which the vegetation was allowed to respond to simulated future climate changes without taking into account the potential for CO_2 fertilization to increase tree productivity and vegetation cover, dust emissions increased by 17% in the ECHAM4 run and were reduced by only 7% in the HADCM3 run (Table 2), which reflects the potential importance of CO2 fertilization for decreasing dust source areas.

[10] We also computed the change in dust emissions assuming that there might be increases in the extent of agricultural areas (Table 2). We used two cultivation scenarios [*Alcamo et al.*, 1998] representing maximum (A2)

Table 2. Simulated Future Changes in Atmospheric Dust Loading

	ECHAM4		HADCM3	
	vs. modern natural	vs. modern total	vs. modern natural	vs. modern total
Natural sources only	+9%	-	−19%	-
Natural sources, no physiological impact of CO_2	+17%	-	−7%	-
Natural and minimum (B1) increase in agricultural areas	+21%	+10%	−9%	−17%
Natural and maximum (A2) increase in agricultural areas	+24%	+12%	−8%	−16%
Natural and improved cultivation practices	+14%	+2%	−19%	−26%

Simulations are based on future climate simulations made with two climate models (ECHAM4 and HADCM3) driven by the IPCC IS92a greenhouse gas scenario. (Modern natural emissions: 1800 Tg/yr, modern total emissions: 1920 Tg/yr.)

and minimum (B1) estimates of increases in agricultural areas between now and 2050, and assumed maximally increased emissions from agricultural compared to natural areas by using the derived correction factors from KG01. Dust emissions in the ECHAM4-driven simulation increased from 9% (natural sources) to between 21% (B1 scenario) and 24% (A2 scenario, Figure 2d) when emissions from anthropogenic soils are included. The reduction in emissions shown in the HADCM3-driven simulation with natural sources (−19%) is less when potential expansion of agricultural sources is taken into account (−8%, Scenario A2, Figure 2f). In the simulations, increased agriculture acts to increase dust emissions, but the effect is never large enough to counter the effects of climate change.

[11] Good cultivation practices and irrigation can reduce dust emissions in drylands. Cropland soil losses are reduced 3 to 5-fold, for example, when plant residues cover >30% of the ground [*Papendick*, 1997]. We ran sensitivity simulations to examine the impact of possible improvements in cultivation techniques (Table 2), assuming no expansion in agricultural area and a 3-fold lowering of dust emissions due to improved cultivation methods in North America, Europe, Australia and Asia. The increase in global emissions in 2050(compared to 1970) in the A2 ECHAM4-driven simulation was only 14%, considerably less than the expected 21–24% increase resulting from future expansion of agricultural areas. Improved cultivation resulted in dust emissions comparable to natural emissions in the HADCM3-driven simulation.

4. Conclusions

[12] We estimate that dust from agricultural soils contributes less than 10% to global dust emissions under modern climate conditions, considerably less than previous estimates. These results indicate that dust from agricultural soils, even if significant locally, is not of great importance for the global radiation budget today. Agricultural dust sources may change in the future, but the overall direction of change in future dust emissions is determined by anthropogenically-induced changes in climate and in natural vegetation.

[13] The projected magnitude in changes in dustiness as suggested by these simulations is less than the 60% decrease predicted by *Mahowald and Luo* [2003]. Such estimates of future changes in dust emissions are clearly model-dependent. Our future simulations do not incorporate climate feedbacks, such as the impacts of changed vegetation and atmospheric dust loadings on climate, which may be important to include in future studies.

[14] Agricultural regions are not the only source of anthropogenic dust. We have not considered possible changes in sources through deforestation, but such areas probably contribute <10% to anthropogenic dust overall [*Tegen and Fung*, 1995]. We have also not considered urban dust (e.g., from construction), dust emissions from dirt roads and military operations in desert areas, but the influence of these sources is likely to be local and relatively small at global scale. Changes in soil hydrology by irrigation could also change the dust source areas, which may be of particular importance in topographic depressions that are preferential source areas for dust emission; this possible effect needs to be further investigated. Uncertainties about the role of dust in future climate are caused by our current inability to determine the direction of climate-induced change in dust-emissions in response to increases in greenhouse gas concentrations.

[15] **Acknowledgments.** This work is a contribution to the TRACES initiative of the International Geosphere-Biosphere Programme, and to the DEKLIM program funded by the German Ministry of Science (BMBF). The ECHAM future climate scenario simulations were provided by the German Climate Computing Center (DKRZ) in Hamburg, Germany. The HADCM3 data has been supplied by the Climate Impacts LINK Project (DEFRA Contract EPG 1/1/124) on behalf of the Hadley Centre and U.K. Meteorological Office. We thank S. Engelstaedter for providing the DSF data set and analysis programs, and C. Zender for his helpful review.

References

Alcamo, J., R. Leemans, and E. Kreileman (Eds.) (1998), *Global change scenarios of the 21st century: Results from the IMAGE 2.1 model*, 296 pp., Pergamon, New York.

Engelstaedter, S., K. E. Kohfeld, I. Tegen, and S. P. Harrison (2003), Controls of dust emissions by vegetation and topographic depressions: An evaluation using dust storm frequency data, *Geophys. Res. Lett.*, *30*, 1294, doi:10.1029/2002GL016471.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson (Eds.) (2001), *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, 881 pp., Cambridge Univ. Press, New York.

Johns, T. C., J. M. Gregory, W. J. Ingram, C. E. Johnson, A. Jones, J. A. Lowe, J. F. B. Mitchell, D. L. Roberts, D. M. H. Sexton, D. S. Stevenson, S. F. B. Tett, and M. J. Woodage (2003), Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios, *Clim. Dyn.*, *20*, 583–612.

Kaplan, J. O., et al. (2003), Climate change and Arctic ecosystems: 2, Modeling, paleodata-model comparisons, and future projections, *J. Geophys. Res.*, *108*, 8171, doi:10.1029/2002JD002559.

Klein Goldewijk, K. (2001), Estimating global land use change over the past 300 years: The HYDE Database, *Global Biogeochem. Cycles*, *15*(2), 417–433.

Knorr, W., and M. Heimann (1995), Impact of drought stress and other factors on seasonal land biosphere CO2 exchange studied through an atmospheric tracer transport model, *Tellus*, *47B*, 471–489.

Mahowald, N. M., and C. Luo (2003), A less dusty future?, *Geophys. Res. Lett.*, *30*, 1903, doi:10.1029/2003GL017880.

Mahowald, N. M., C. S. Zender, C. Luo, D. Savoie, O. Torres, and J. del Corral (2002), Understanding the 30-year Barbados desert dust record, *J. Geophys. Res.*, *107*, 4561, doi:10.1029/2002JD002097.

Papendick, R. I. (Ed.) (1997), *Farming with the wind: Best management practices for controlling wind erosion and air quality on Columbia Plateau croplands*, 77 pp., Wash. State Univ. Coll. of Agricult. and Home Econ., Pullman, WA.

Prospero, J. M., P. Ginoux, O. Torres, S. E. Nicholson, and T. E. Gill (2002), Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product, *Rev. Geophys.*, *40*, 1002, doi:10.1029/2000RG000095.

Ramankutty, N., and J. A. Foley (1999), Estimating historical changes in global land cover: Croplands from 1700 to 1992, *Global Biogeochem. Cycles*, *13*(4), 997–1027.

Roeckner, E., L. Bengtsson, J. Feichter, J. Lelieveld, and H. Rodhe (1999), Transient climate change with a coupled atmosphere-ocean GCM including the tropospheric sulfur cycle, *J. Climate*, *12*, 3004–3032.

Sokolik, I. N., and O. B. Toon (1996), Direct radiative forcing by anthropogenic airborne mineral aerosols, *Nature*, *381*, 681–683.

Tegen, I., and I. Fung (1995), Contribution to the atmospheric mineral aerosol load from land surface modification, *J. Geophys. Res.*, *100*(D9), 18,707–18,726.

Tegen, I., S. P. Harrison, K. E. Kohfeld, I. C. Prentice, M. Coe, and M. Heimann (2002), Impact of vegetation and preferential source areas on global dust aerosol: Results from a model study, *J. Geophys. Res.*, *107*, 4576, doi:10.1029/2001JD000963.

Werner, M., I. Tegen, S. P. Harrison, K. E. Kohfeld, I. C. Prentice, Y. Balkanski, H. Rodhe, and C. Roelandt (2002), Seasonal and interannual variability of the mineral dust cycle under present and glacial climate conditions, *J. Geophys. Res.*, *107*, 4744, doi:10.1029/2002JD002365.

S. P. Harrison, K. E. Kohfeld, I. Tegen, and M. Werner, Max Planck Institute for Biogeochemistry, 07701 Jena, Germany. (itegen@bgc-jena.mpg.de)