ADJOINT INVERSION OF ATMOSPHERIC DUST SOURCES FROM SATELLITE OBSERVATIONS

by

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ADJOINT INVERSION OF ATMOSPHERIC DUST SOURCES

FROM SATELLITE OBSERVATIONS

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Abstract to be filled ...

DEDICATION

To the memory of my grandparents

Zhaoxiang Xu

and

Shi Zhao Xu

ACKNOWLEDGMENTS

Arma virumque cano, Troiae qui primus ab oris Italiam, fato profugus, Laviniaque venit litora, multum ille et terris iactatus et alto vi superum saevae memorem Iunonis ob iram; multa quoque et bello passus, dum conderet urbem, inferretque deos Latio, genus unde Latinum, Albanique patres, atque altae moenia Romae.

GRANT INFORMATION

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CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

1.1.1 Impacts of Atmospheric Dust Aerosol

Atmospheric aerosols play a crucial role in the global climate change. They affect earth energy budget directly by scattering and absorbing solar and terrestrial radiation, and indirectly through altering the cloud formation, lifetime, and radiative properties [Haywood and Boucher, 2000; Ramanathan et al., 2001]. However, quantification of these effects in the current climate models is fraught with uncertainties. The global average of aerosol effective radiative forcing (ERF) were estimated to range from -0.1 to -1.9 Wm2 with the best estimate of -0.9 Wm2 [Boucher et al., 2013], indicating that the cooling effects of aerosol might counteract the warming effects of 1.820.19 Wm2 caused by the increase of carbon dioxide since the industrial revolution [Myhre et al., 2013]. The climate effects of aerosol particles depend on their geographical distribution, optical properties, and efficiency as cloud condensation nuclei (CCN). Key quantities pertain to the aerosol optical and cloud-forming properties include particle size distribution (PSD), chemical composition, mixing state, and morphology [Boucher et al., 2013]. While the daily aerosol optical depth (AOD) can be well measured from current satellite and ground-based remote sensing instrumentations [e.g., Holben et al., 1998; Kaufman et al., 2002], the accurate quantification of aerosol ERF is in no small part hindered by our limited knowledge about the aerosol PSD and refractive index (describing chemical composition and mixing state). To fully understand the role of aerosol particles in the global climate change, further development in observations along with retrieval algorithms for these aerosol microphysical properties from different platforms are thus highly needed [Mishchenko et al., 2004], and the focus of this two-part series study is the characterization of aerosol properties from ground-based passive remote sensing

1.1.2 Dust Emission and its Parameterizations

Koven and Fung [2008] have investigated ...

Source function can be estimated based topography [*Ginoux et al.*, 2001],

1.1.3 Observations of Dust from Space

1.2 Main Goals of This Work

1.3 Organization of This Dissertation

CHAPTER 2

MODELING OF ATMOSPHERIC DUST

2.1 Modeling of Dust Emission

2.1.1 Physical Parameterization of the Dust Emission

The dust emission, aerolian wind erosion that results in production of mineral aerosols from soil grains, involves complex and nonlinear processes that are governed by the meteorology as well as by the state and properties of the land surfaces. Laboratory [Iversen and White, 1982] and field [Shao et al., 1996; Zender et al., 2003] wind tunnel studies suggested that dust is primiarily injected into the atmosphere during the sandblasting caused by the saltation bombardment [Alfaro and Gomes, 2001; Grini et al., 2002]. The clay- and silt-sized soil particles have strong inter-cohesive force... The saltation of sand-sized particles ... requires least threshold of wind speed...

The most important factors include wind friction velocity and its threshold for saltation, vegetation cover, soil minerology, and surface soil moisture.

In this study, the physical parameterization of dust emission is taken from a Dust Entrainment and Deposition (DEAD) model developed by Zender et al [2003a]. The DEAD scheme calculates the wind friction threshold (u_{*t}) as a function of the Reynolds number following Iversen and White [1982] and Marticorena and Bergametti [1995]. Three processes are also considered to modify the u_{*t}: the drag partitioning owing to the momentum captured by nonerodible roughness elements, the Owen effect, and moisture inhition. The horizontal saltation flux (Q_s) that is defined as the vertical integral of the stream-wise soil flux density is calculated following the theory of White [1979]:

$$Q_s(u_*, u_{*t}) = \frac{c_s \rho}{g} u_*^3 \left(1 - \frac{u_{*t}}{u_*}\right) \left(1 + \frac{u_{*t}}{u_*}\right)^2, \tag{2.1}$$

where, $c_s = 2.61$, ρ is the air density at surface level, and $u*$ is the wind friction velocity. Thus, it assumes the saltaion flux is quasi-lienarly the u_*^3 when u_* exceeds the u_{*t}. It also neglect the dependence of total Q_s on the soil size.

the total vertical mass flux of dust into transport bin j is

$$E_{d,j} = \begin{cases} T_0 A_m S \alpha Q_s \sum_{i=1}^{3} M_{i,j} & \text{if } u_* \geq u_{*t}, \\ 0 & \text{if } u_* < u_{*t}, \end{cases} \tag{2.2}$$

where, T_0 is a tuning factor chosen to adjust the global amount, A_m is the fraction of bare solil exposed in a model grid cell, S is called "erodiblity" or "perferential source function", α is the sandblasting mass efficiency factor which depends on the mass fraction of clay particles in the parent soil, and $M_{i,j}$ indicates the mass fraction of ith source mode carried into the jth transport mode.

2.1.2 Development of the Wind Speed Distribution

In order to incorporate the variability of wind speed due to the subgrid scale circulations, we introduce a probability density function (PDF) of the wind speed within each grid box. The dust emission is computed according to the fraction of the PDF that exceeds the threshold value:

$$E_d = \int_{u_{*t}}^{\infty} E(u_*) p(u_*) du_*. \tag{2.3}$$

Where $E(u_*)$ is the emission as a function of the surface wind friction velocity, and $p(u_*)$ is the PDF of u_* within the grid box.

The PDF for surface wind speeds can be represented by a Weibull distribution [Justus et al., 1978] and has been used in recent studies [e.g., Grini and Zender, 2004; Grini et al., 2005; Ridley et al., 2013] to charaterize the subgrid dust emissions. The PDF of a Weibull random variable x is described by a shape factor k and a scale factor c:

$$p(x;c,k) = \frac{k}{c}(x/c)^{k-1}\exp\left[-(x/c)^k\right], \text{ for } x > 0. \tag{2.4}$$

One of the advantages in using the Weibull PDF is that it is analytically integrable with the cumulative distribution function:

$$P(x \leq x_1; c,k) = 1 - \exp\left[-(x/c)^k\right]. \tag{2.5}$$

Based on above cumulative function, we cut off wind speeds with a minimum and a maximum wind speed to retain the central 98% of the wind PDF. As a result, the lower and upper limits of wind speed are respectively:

$$x_l = c\left[-\ln 0.99\right]^{\frac{1}{k}} \tag{2.6}$$

$$x_u = c\left[-\ln 0.01\right]^{\frac{1}{k}} \tag{2.7}$$

Parameters k and c can be estimated from the statistical mean $\bar{x}$ and variance σ^2 (of x), since they are related to $\bar{x}$ and σ^2:

$$\bar{x} = c\Gamma(1+1/k) \tag{2.8}$$

$$\sigma^2 = c^2\left[\Gamma(1+2/k) - \Gamma^2(1+1/k)\right] \tag{2.9}$$

Where $\Gamma()$ is a gamma function. According to Justus et al. [1978], k and c can be best estimated by:

$$k = (\sigma/\bar{x})^{-1.086} \tag{2.10}$$

$$c = \bar{x}[\Gamma(1+1/k)]^{-1} \tag{2.11}$$

Thus, the only parameter that must be supplied beyound the mean wind speed is the variance (σ^2) of subgrid wind speeds within the grid box. Cakmur et al [2004] calculated the σ^2 by incorporating information from the parameterizations of the planetary boundary layer along with dry and moist convection. Here, we follow Grini and Zender [2004] and Grini et al [2005] that assumed an approximation of k based on Justus et al. [1978]:

$$k = 0.94 u_*^{\frac{1}{2}} \tag{2.12}$$

Finally, the dust emission flux is calculated by

$$E_{d,j} = A_m S \alpha \left(\sum_{i=1}^{3} M_{i,j} \right) \frac{c_s \rho}{g} \int_{u_{*t}}^{u_{*u}} u_*^b \left(1 - \frac{u_{*t}}{u_*}\right) \left(1 + \frac{u_{*t}}{u_*}\right)^2 p(u_*) du_*. \tag{2.13}$$

Where u_{*u} is the upper limit of wind speed determined by equation (2.7).

2.2 Modeling of Dust Transport and Deposition

CHAPTER 3

ADJOINT MODELING DEVELOPMENT

3.1 GEOS-Chem Adjoint

3.2 Implement Adjoint of DEAD

In simple, The dust emission flux considering subgrid wind speeds in equation (2.13) can be writen

$$E_{d,j} = C_j S' \int_{u_{*t}}^{u_{*u}} Q_s(u_*, u_{*t}, b) p(u_*) du_*, \tag{3.1}$$

where $S' = S\alpha$, and $C_j = A_m \sum_{i=1}^{3} M_{i,j}$. We combine the erodibility S and sandblasting factor α, because both of them not only are related to the soil texture but also describe the strength efficiency of dust emission. Given the the state of land surface and the properties of surface soil, the dust emission is a function of S', b, and u_{*t}.

Here we implement the adjoint calculation for three parameters, i.e., S', b, and u_{*t}. This implementation reqiures the partial derivatives of $E_{d,j}$ with respect to these parameters (when $u_* \geq u_{*t}$):

$$\frac{\partial E_{d,j}}{\partial S'} = \frac{E_{d,j}}{S'}, \tag{3.2}$$

$$\frac{\partial E_{d,j}}{\partial b} = C_j S' \int_{u_{*t}}^{u_{*u}} \frac{\partial Q_s}{\partial b} p(u_*) du_*, \tag{3.3}$$

$$\frac{\partial E_{d,j}}{\partial u_{*t}} = C_j S' \int_{u_{*t}}^{u_{*u}} \frac{\partial Q_s}{\partial u_{*t}} p(u_*) du_*. \tag{3.4}$$

These gradients of Q_s in equations (3.3 and 3.4) can be calculated by

$$\frac{\partial Q_s}{\partial b} = Q_s(u_*, u_{*t}, b) \ln u_* \tag{3.5}$$

$$\frac{\partial Q_s}{\partial u_{*t}} = \frac{c_s \rho}{g} u_*^b \left[\frac{1}{u_*} - \frac{2u_{*t}}{u_*^2} - \frac{3u_{*t}^2}{u_*^3} \right] \tag{3.6}$$

CHAPTER 4

SOME TABLES AND FIGURES

First	Last
Ned	Hummel
Ned	Hummel
Ned	Hummel

Table 4.1: Arma virumque cano, Troiae qui primus ab oris Italiam, fato profugus, Laviniaque venit litora, multum ille et terris iactatus et alto vi superum saevae memorem Iunonis ob iram

✓	Foo
✓	Foo
✓	Foo

Table 4.2: Arma virumque cano, Troiae qui primus ab oris Italiam, fato profugus, Laviniaque venit litora, multum ille et terris iactatus et alto vi superum saevae memorem Iunonis ob iram

Figure 4.1: Arma virumque cano, Troiae qui primus ab oris Italiam, fato profugus, Laviniaque venit litora, multum ille et terris iactatus et alto vi superum saevae memorem Iunonis ob iram

CHAPTER 5

SOME MATH

This is a triviality, but we include it for completeness.

$$\int_0^\infty f(x)\,dx = \begin{cases} 1 & \text{if } f = \delta, \\ 0 & \text{if } f = 0. \end{cases} \tag{5.1}$$

Here is an aligned set of equations.

$$\begin{aligned} f(x) &= f(x) \cdot 1 && (5.2) \\ &= f(x) \cdot (2-1) && (5.3) \\ &= f(x) && (5.4) \end{aligned}$$

The clever step is (5.3).

APPENDIX A

TESTING, 1, 2, 3, . . .

This has been a test of the thesis typesetting system. Had this been an actual thesis, this would have been preceded by an actual thesis.

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