

Modeling Patagonian Dust and Soluble Iron Deposition to the Southern Ocean: Application of GEOS-Chem

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1. Introduction

Aeolian dust deposition has proven to be a critical source of iron (Fe) to high nitrate low chlorophyll (HNLC) oceanic regions. Out of the three main HNLC areas (subarctic north Pacific, equatorial Pacific, and the Southern Ocean) the Southern Ocean (SO) is suggested to be the largest region where marine productivity is limited by the micronutrient Fe (Watson et al., 2000). The importance of this region is reflected in a hypothesis that the glacial-interglacial change of atmospheric CO₂ can be attributed to changes in the atmospheric dust-Fe supply to the SO (Martin and Fitzwater, 1988). Recently this theory has been challenged by pointing out the importance of marine processes in the supply of Fe to the surface ocean (Meskhidze et al., 2007; Blain et al., 2007). The role of aeolian Fe deposition for marine ecosystem productivity is further complicated by the fact that ocean productivity is influenced not by the total amount of dust-laden Fe, but the portion of Fe that is in a soluble (or bioavailable) form (Jickells et al., 2005 and references therein). Today there are very few studies that can help constraining mineral dust and dust-laden Fe deposition to the SO. Also seasonality and transport pathways for the source regions contributing mineral dust to the SO remain to be poorly defined.

In this study we apply GEOS-Chem, a global chemistry-transport model, to estimate fluxes of mineral dust and dissolved Fe (DFe) deposited to the South Atlantic Ocean (SAO). Patagonia is considered as the major source (contributing up to 90% of total dust) of aeolian Fe deposited to the SAO (Gaiero et al., 2006). Therefore, the objective of this study is to better quantify Patagonia's influence on dust and DFe fluxes to the surface waters of the SAO. Key aspects addressed here are the dust source locations and emission rates in Patagonia, seasonality, total fluxes of dust and soluble Fe to the SAO,

and the model's ability to capture the episodic dust events from Patagonia.

2. Methods

GEOS-Chem is a global chemistry transport model (CTM) driven by assimilated meteorological fields from the Goddard Earth Observing System (GEOS) of the NASA Global Modeling Assimilation Office (Bey et al., 2001). To evaluate dust emission and transport we use the latest version of GEOS-Chem (v8-01-01). The model is driven with GEOS-5 meteorological fields at a 2° x 2.5° (latitude-longitude) grid resolution and 47 vertical levels. For dust mobilization, GEOS-Chem is using the DEAD (Dust Entrainment and Deposition) scheme (Zender et al., 2003). The DEAD scheme was shown to capture much of the amplitude and seasonal cycle in dust climatologies at surface sites of the North Pacific Ocean (Fairlie et al., 2006). For the analysis of dust mobilization, transport, and deposition from Patagonia we conducted a yearlong model simulation between October 2006 and September 2007. This time period was selected to take advantage of the most recent meteorological fields (GEOS-5) available for the model. Simulation period also allowed us to capture two contrasting dust advection seasons: high dust of austral summer and the low dust of winter along with daily 24-hour averaged dust fluxes.

We have recently implemented an Fe dissolution module Meskhidze et al. (2005) into the new version of GEOS-Chem. However, due to the large simulation time required for running the model with the full chemistry, the DFe modeling results reported here are for the time period between August 2001 and February 2002 using different version of GEOS-Chem (v7-03-06). This version was shown to be in a good agreement with the experimental data for the deposition of bioavailable Fe in subarctic North

Pacific Ocean, downwind from east Asia (Solmon et al., 2008).

To accurately simulate DFe deposition to the SAO, Patagonian dust characteristics such as emissions, transport, and deposition values must be treated correctly. Emission location and source strength were averaged annually and compared to past model simulations (Li et al., 2008; Tegen et al., 2004). Comparison of GEOS-Chem yearly averaged dust deposition to past studies (Wagner et al., 2008; Li et al., 2008) allows us to assess the model performance for mineral dust fluxes to SAO. Comparison of GEOS-Chem results to other modeling studies is used here due to the severe lack of in situ data in this part of the world ocean. To estimate total amount of dust advected from Patagonia, daily, monthly, and yearly averaged dust fluxes are calculated along the Patagonia coast.

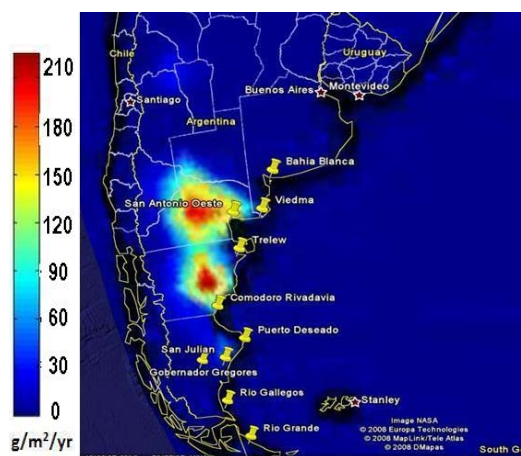


Figure 1. GEOS-Chem average dust source location and emission rates. Yellow markers indicate dust report locations available for the region. Stations used in the vicinity of large dust source regions are (from top to bottom) Bahia Blanca, Viedma, San Antonio Oeste, Trelew, and Comodoro Rivadavia.

3. Results

3.1 Dust Mobilization and Source Regions

An accurate dust mobilization scheme is the first step for reasonable representation of long range transport and deposition of dust (Zender et al., 2003). Comparison of GEOS-Chem predicted dust source locations and emission rates with past modeling studies showed consistency in model predicted dust mobilization regions in Patagonia. GEOS-Chem performance was further analyzed by overlaying

the model predicted dust emission regions over the Google Earth topography maps. Analyses revealed that the strongest dust sources were dry lake/river beds and low-lying topographical regions.

It has been proposed, that the major fraction of desert dust from Patagonia may be deposited to the SAO in just a few episodes of the large dust outbreaks (Mahowald et al., 2008). Therefore, large episodic dust storms in Patagonia could have a profound effect on the total amount and spatial pattern of dust fluxes to the SAO. The ability of GEOS-Chem to capture individual dust events was evaluated using surface dust reports from Patagonia (<http://www.wunderground.com/global/AG.html>). The stations chosen here (see Figure 1) are located near the model predicted strongest dust source regions. Visibility reports from these stations were compared to model predicted dust column concentrations for the qualitative evaluation of the model's ability to capture individual dust events.

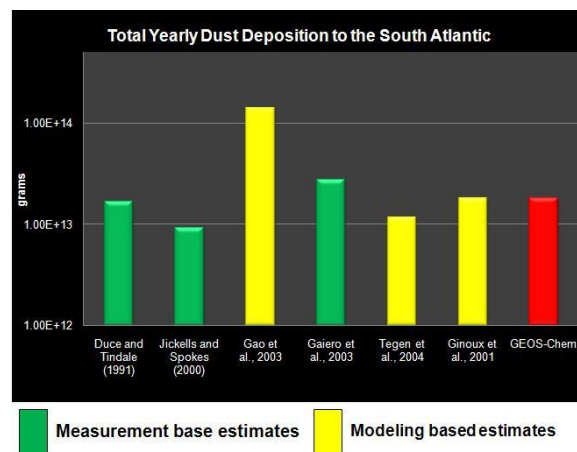


Figure 2. Displays several modeling and measurement based estimates of total dust deposition to the South Atlantic and SO. GEOS-Chem (red) predicted annual deposition compares well with past estimates.

3.2 Dust Deposition to the SAO

GEOS-Chem predicted yearly averaged dust deposition to the SAO is $\sim 15 \text{ Tg yr}^{-1}$. In Figure 2 we compare this value to past modeling and measurement studies constraining the SAO domain. This figure shows that GEOS-Chem predicted magnitude of dust deposition compares well with most of the past studies, except one by Gao et al. (2003) that predicted

dust fluxes almost an order a magnitude higher compared to all other studies.

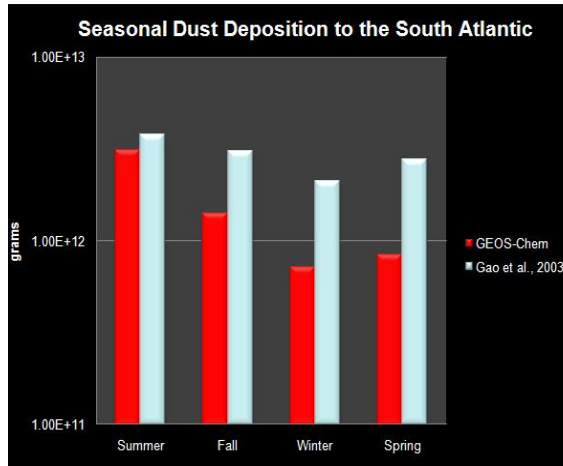


Figure 3. Seasonal dust deposition to the SAO simulated by GEOS-Chem (red) and compared to Gao et al., 2003 (blue).

In Figure 3 seasonal dust deposition to the SAO simulated by GEOS-Chem is compared to Gao et al. (2003). This figure shows that both models capture dust deposition seasonality correctly, i.e., show the highest values for austral summer and the lowest for winter. Overall, GEOS-Chem simulated large seasonal difference (~65%) in mineral dust deposition to the SAO. Further model evaluation using in-situ measurement is needed to better constrain dust transport and deposition to the SAO.

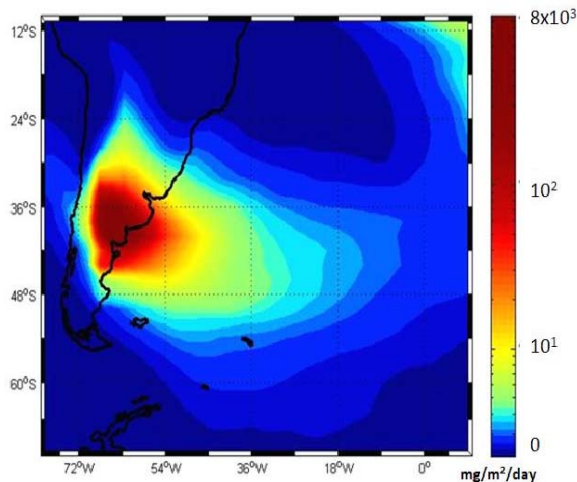


Figure 4. GEOS-Chem predicted yearly averaged dust deposition to the SAO.

In addition to total yearly and seasonal amounts of deposited dust, transport path and

spatial variability of fluxes are also important factors in dust deposition studies. Figure 4 demonstrates yearly averaged (October 2006 and September 2007) dust deposition over the modeled domain. The spatial pattern of dust deposition is consistent with past studies (e.g., Wagner et al., 2008; Li et al., 2008). Figure 5 shows a time series of GEOS-Chem predicted column dust concentration and corresponding surface dust reports in Patagonia. The data markers indicate days in which dust storms were reported in the station's visibility report. We chose to concentrate on the austral summer months due to dust storms being more frequent and in larger magnitude compared to the rest of the year. As seen from Figure 5 GEOS-Chem predicted elevated dust concentrations on almost every day in which a dust storm was reported by one (or more) station. The only large discrepancy was on February 4th, 2007 (black circle). During this time none of the stations reported visible increase in dust abundance in the atmosphere, while model predicted elevated dust concentrations. Plotting dust vertical profiles over the station locations, allowed us to elucidate a possible cause for such discrepancy. Vertical profiles of dust demonstrated (not shown) that the dust plume was entrained into the free troposphere and transported over the stations at high altitude. While the model simulated large column dust concentrations, very little dust was present at the surface. Therefore, the surface dust concentrations at the stations may have not been large enough to be reported as a considerable dust event. While being only a qualitative comparison, the model showed a sound ability to reproduce episodic dust events that compared well to the station reported dust storms. Over the entire simulation period, GEOS-Chem captured the majority (over 75%) of reported dust storms.

3.3 Dissolved Fe fluxes to the SAO

Past modeling studies show, that atmospheric transport and transformation of aerosols could play considerable role in dust-Fe solubilization. However, to simulate the chemical evolution of dust plumes and quantify DFe fluxes to the SAO, mineralogical composition of Patagonian dust needs to be considered. The initial mineral content of the dust particles was designed to be representative of the transportable fraction of mineral dust from

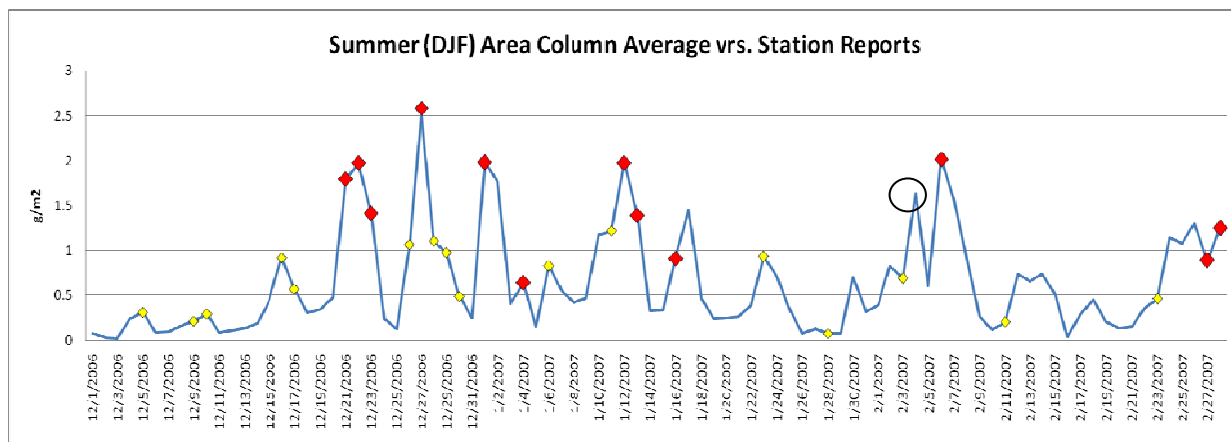


Figure 5. GEOS-Chem predicted column dust concentrations compared to ground based dust reports from Patagonia. The blue line shows the GEOS-Chem column dust concentration over the Patagonian station locations. Red points indicate more than one station reporting dust storms, and yellow points indicate days in which at least one station reported dust.

Patagonia. With such prescribed mineralogy (see Table 1) of windblown dust from Patagonia and full gas- and aqueous-phase chemistry, GEOS-Chem with dust mobilization module (GEOS-Chem/DfFe) allows prognostic evaluation of transport and deposition of soluble Fe in the SAO.

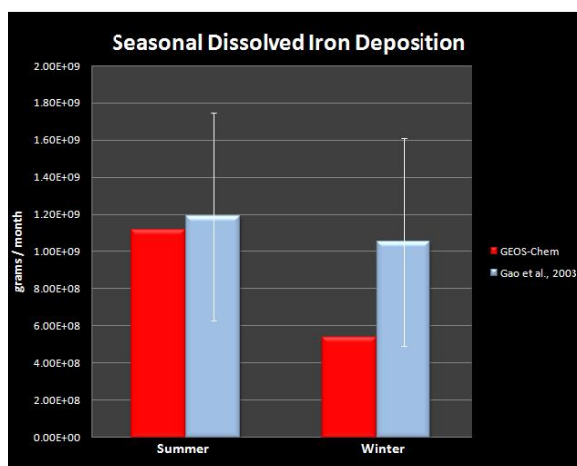


Figure 6. GEOS-Chem simulated monthly averaged DfFe deposition rates (g month^{-1}) in comparison with Gao et al. (2003) with assumed 3% of DfFe. Error bars represent the range in DfFe fluxes with iron solubility range between 1 and 6% proposed by Gao et al. (2003).

Figure 6 compares GEOS-Chem simulated DfFe with that of Gao et al. (2003). This figure shows that an average DfFe deposition rates (g month^{-1}) predicted by GEOS-Chem for November 2001 – January 2002, and July – September, 2001 were $\sim 1.2 \times 10^9 \text{ g month}^{-1}$ and $\sim 5.4 \times 10^8 \text{ g month}^{-1}$

respectively. Figure 6 shows that GEOS-Chem predicted seasonal trend in DfFe deposition to the SAO is consistent with Gao et al. (2003); both modeling results show higher amounts of DfFe being deposited to SAO during summer than winter months. However, the seasonal difference in DfFe deposition predicted by GEOS-Chem is larger than estimated in Gao et al. (2003). This difference in seasonal trends is reflecting the variability in total dust deposition predicted by GEOS-Chem (see Figure 3). With dust-laden iron being prescribed an initial solubility of 0.45% (Solmon et al., 2008), GEOS-Chem is likely to deposit larger concentrations of DfFe during periods of increased dust fluxes. The initial solubility of dust laden iron is not well constrained and remains as a large source of uncertainty in DfFe flux estimates. To further

Table 1 Patagonian Top Soil Mineralogy

Minerals	In Soil, % wt ^a	
	In Silt	In Clay
Anhydrite CaSO ₄	6 ⁺	0
Calcite CaCO ₃	4	0 ⁺
Plagioclase Albite – NaAlSi ₃ O ₈ Microcline – KAlSi ₃ O ₈	28	8
Illite K _{0.6} Mg _{0.25} Al _{2.3} Si _{3.5} O ₁₀ (OH) ₂	18 ⁺	13
Smectite/Montmorillonite Na _{0.6} Al _{1.4} Mg _{0.6} Si ₄ O ₁₀ (OH) ₂ · 4H ₂ O	7 ⁺	62
Hematite Fe ₂ O ₃	5	3
Quartz SiO ₂	27	7
Kaolinite Al ₂ Si ₂ O ₅ (OH) ₄	5 ⁺	7
Total	100	100

^a Mineralogical composition were largely based on Gaiero et al. (2003), Smith et al. (2003), and Ramsperger et al. (1998).

⁺ Assumed generic dust composition due to insufficient data.

validate GEOS-Chem results for the deposition of bioavailable Fe to the SAO, in situ measurements for dissolved Fe concentration in Patagonian dust aerosols are required. None the less, preliminary results of this study show that GEOS-Chem/DfFe provides good foundation in which future improvements to DfFe module can be conducted.

4. Conclusion

This modeling study shows that GEOS-Chem was able to provide a good base model for the prognostic evaluation of dissolved Fe fluxes to the SAO downwind from Patagonia. Patagonia's dust emission, transport, and deposition were quantified and analyzed during the period of October 2006 to September 2007. Through comparison with existing model results for the SAO domain we show that GEOS-Chem is capable of simulating total fluxes of mineral dust advected from Patagonia. Using qualitative agreement with remotely sensed images of dry river/lake beds and ground based station reports of dust outbreaks, dust source regions and seasonal and daily variations of dust concentrations were also assessed. In this study we estimate total dust deposition to the SAO to be $\sim 15 \text{ Tg yr}^{-1}$. This value, along with seasonal dust transport and deposition pattern, is consistent with past studies. We also show that GEOS-Chem was capable of capturing over 75% of station reported dust storms. During the low dust season (June - August 2006) we show that the majority of mineral dust mass (>65%) was deposited to the SAO in isolated, episodic events. While during the high dust season (December 2006 - February 2007), due to large background dust concentration, only $\sim 27\%$ of dust got deposited to the SAO during the top 5% of large dust outbreaks. Therefore the ability of GEOS-Chem to capture individual dust outbreaks is important throughout the year, especially during times of low background dust concentrations and less frequent dust events.

One of the main interests for mineral dust deposition to the SAO is the concentration of bioavailable Fe that is a limiting micronutrient for ocean biota. Our preliminary modeling result using GEOS-Chem/DfFe suggest a total of $\sim 6 \times 10^9$ grams DfFe was contributed to the SAO from Patagonian dust from July, 2001 – January, 2002. This result suggests that soluble Fe fraction is $\sim 1.5\%$ of total dust-laden Fe from Patagonia deposited to the SAO. To better elucidate spatial and temporal variation of DfFe

fluxes to the SAO and the role of aeolian Fe for ocean productivity in this HNLC region, a full year simulation using the latest version of GEOS-Chem (v8-01-01) with implemented DfFe module is presently under way.

In this study, GEOS-Chem/DfFe demonstrated the ability to simulate dust and DfFe transport and deposition to the SAO that is consistent with previous modeling efforts and measurement data. Our future model development will focus on the improvements to Fe dissolution scheme by addition of combustion (industrial and biomass burning) iron sources, photo-reductive dissolution of iron containing minerals, and photochemical cycling of Fe (II) and Fe (III). This will allow us to estimate the effects of future changes such as increased pollution and variability in dust emissions, on DfFe fluxes to the SAO.

References

- Bey, I., et al. (2001), Global modeling of tropospheric chemistry with assimilated meteorology: model description and evaluation. *J. Geophys. Res.*, 106, 23073–23096.
- Blain et al. (2007). Effect of natural iron fertilization on carbon sequestration in the Southern Ocean. *Nature*. 446, doi: 10.1038/nature05700.
- Duce, R. A., and N. W. Tindale (1991), Atmospheric transport of iron and its deposition in the ocean, *Limnol. Oceanogr.*, 36, 1715-1726.
- Fairlie, T. D., J. Jacobs, and R. J. Rokjin (2006), The impact of transpacific transport of mineral dust in the United States, *Atmos. Env.*, 41, 1251–1266.
- Gaiero, D. M., J. L. Probst, P. J. Depetris, S. M. Bidart, and L. Leleyter (2003), Iron and other transition metals in Patagonian riverborne and windborne materials: Geochemical control and transport to the southern Atlantic Ocean, *Geochimica et Cosmochimica Acta*, 67(19), 3603-3623, doi: 10.1016/S0016-7037(03)00211-4.
- Gaiero, D. M., F. Brunet, J. L. Probst, and P. J. Depetris (2006), A uniform isotopic and chemical signature of dust exported from Patagonia: Rock sources and occurrence in southern environments, *Chem. Geo.*, 238, 107-120, doi: 10.1016/j.chemgeo.2006.11.003.
- Gao, Y., Y. G. Kaufman, D. Tanre, D. Kolber, and P.G. Falkowski (2001), Seasonal distributions of aeolian iron fluxes to the global ocean, *J. Geophys. Res.*, 1, 29-32.
- Gao, Y., S. M. Fan, and J. L. Sarmiento (2003) Aeolian iron input to the ocean through precipitation scavenging: A modeling perspective and its implication for natural iron fertilization in the ocean, *J. Geophys. Res.*, 108, doi: 10.1029/2002JD002420.
- Generoso, S., I. Bey, M. Labonne, and F. M. Breon (2008) Aerosol vertical distribution in dust outflow over the Atlantic: Comparison between GEOS-Chem and CALIPSO, in press.
- Jickells, T.D., and L.J. Spokes (2000), Atmospheric iron inputs to the ocean, in: *Biogeochemistry of Iron in Seawater* (Eds. D. Turner and K.A. Hunter), John Wiley and Sons.
- Jickells et al. (2005), Global Iron Connections Between Desert Dust, Ocean Biogeochemistry, and Climate, *Science*, 308, 67-71.

- Li, F., P. Ginoux, and V. Ramaswamy (2008), Distribution, transport, and deposition of mineral dust in the Southern Ocean and Antarctica: Contribution of major sources, *J. Geophys. Res.*, *113*, D10207, doi: 10.1029/2007JD009190.
- Loye-Pilot M., J. Martin, and J. Morellit (1986). Influence of Saharan dust on the rain acidity and atmospheric input to the Mediterranean, *Nature*, *321*, 427–28.
- Martin, J. H., and S. E. Fitzwater (1988), Iron-deficiency limits phytoplankton growth in the northeast pacific subarctic, *Nature*, *331*, 341-343.
- Mahowald et al. (2008), Atmospheric Iron Deposition: Global Distribution, Variability, and Human Perturbations, *Annu. Rev. Mar. Sci.*, *1*, 245–278.
- Meskhidze, N., W. L. Chameides, and A. Nenes (2005), Dust and pollution: A recipe for enhanced ocean fertilization?, *J. Geophys. Res.*, *110*, D03301, doi: 10.1029/2004JD005082.
- Meskhidze, N., A. Nenes, W. L. Chameides, C. Luo, and N. Mahowald (2007), Atlantic Southern Ocean productivity: Fertilization from above or below?. *Global Biogeochem. Cycles*, *21*, GB2006, doi: 10.1029/2006GB002711.
- Ramsperger, B., N. Peinemann, and K. Stahr (1998), Deposition rates and characteristics of Aeolian dust in the semi-arid and sub-humid regions of the Argentinean Pampa, *J. of Arid Env*, *39*, 467-476.
- Solmon, F., P.Y. Chuang, N. Meskhidze, and Y. Chen (2008), Acidic processing of mineral dust iron by anthropogenic compounds over the north Pacific Ocean., *J. Geophys. Res.*, in press, doi: 10.1029/2008JD010417.
- Smith, J., D. Vance, R. A. Kemp, C. Archer, P. Toms, M. King, and M. Zarate (2003), Isotopic constraints on the source of Argentinian loess – with implications for atmospheric circulation and the provenance of Antarctic dust during recent glacial maxima, *Earth Planet. Sci. Lett.*, *212*, 181-196.
- 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, *J. Geophys. Res.*, *31*, L05105, doi: 10.1029/2003GL019216.
- Zender, C. S., D. Newman, and O. Torres (2003), Spatial heterogeneity in aeolian erodibility: Uniform, topographic, geomorphic, and hydrologic hypotheses, *J. Geophys. Res.*, *108*(D17), 4543, doi: 10.1029/2002JD003039.