Dust and sea surface temperature forcing of the 1930s "Dust Bowl" drought

Benjamin I. Cook,[1,2] Ron L. Miller,[2] and Richard Seager[1]

Received 31 January 2008; revised 10 March 2008; accepted 21 March 2008; published 22 April 2008.

[1] Droughts over the central United States (US) are modulated by sea surface temperature (SST) variations in the eastern tropical Pacific. Many models, however, are unable to reproduce the severity and spatial pattern of the "Dust Bowl" drought of the 1930s with SST forcing alone. We force an atmosphere general circulation model with 1930s SSTs and model-generated dust emission from the Great Plains region. The SSTs alone force a drought over the US similar to observations, but with a weaker precipitation anomaly that is centered too far south. Inclusion of dust radiative forcing, centered over the area of observed wind erosion, increases the intensity of the drought and shifts its center northward. While our conclusions are tempered by limited quantitative observations of the dust aerosol load and soil erosion during this period, our study suggests that unprecedented atmospheric dust loading over the continental US exacerbated the "Dust Bowl" drought. **Citation:** Cook, B. I., R. L. Miller, and R. Seager (2008), Dust and sea surface temperature forcing of the 1930s ''Dust Bowl'' drought, *Geophys. Res. Lett.*, *35*, L08710, doi:10.1029/2008GL033486.

1. Introduction

[2] Droughts in the midlatitudes of both hemispheres are often associated with sea surface temperature (SST) anomalies in the eastern tropical Pacific, specifically the La Nina phase of the El Nino–Southern Oscillation [*Seager et al.*, 2005a]. Examples over North America include droughts during the 1950s and latter part of the 19th century [*Herweijer et al.*, 2006; *Seager et al.*, 2005b], as well as the most recent and ongoing drought in the western US [*Hoerling and Kumar*, 2003; *Seager*, 2007]. Modeling evidence suggests SST forcing was at least partially responsible for the drought during the 1930s known as the "Dust Bowl" [*Schubert et al.*, 2004a, 2004b; *Seager et al.*, 2005b, 2008]. Models, however, have difficulty reproducing the severity and spatial pattern of the Dust Bowl drought, instead producing droughts that, while superficially similar to observations, are too weak and centered in the southwest rather than the central and northern Great Plains as observed [e.g., *Schubert et al.*, 2004a, 2004b; *Seager et al.*, 2005b, 2008]. *Seager et al.* [2008] used millennium long tree ring records to argue that the spatial pattern of the Dust Bowl drought was unique in the era of instrumental observations. This has led to speculation that the drought may have been amplified by land surface feedbacks related to the large-scale land degradation over the Great Plains region during this decade. A consequence of this degradation was massive wind erosion and dust storms on an unprecedented scale [*Seager et al.*, 2008; *Worster*, 1979].

[3] Dust storms were widespread throughout the United States during the 1930s [e.g., *Mattice*, 1935a, 1935b]. High wind erosion resulted from a variety of convergent factors, including low soil moisture from the drought, poor land use practices, and the replacement of drought resistant native grasslands with drought susceptible wheat crops [*Hansen and Libecap*, 2004]. Recent studies have shown the potential for high dust loading in the atmosphere to suppress precipitation [e.g., *Miller and Tegen*, 1998; *Rosenfeld et al.*, 2001]. Dust effectively scatters and absorbs shortwave radiation while absorbing and emitting longwave radiation. By reducing the net radiation into the surface beneath the aerosol layer, dust reduces evaporation and thus precipitation [*Miller and Tegen*, 1998]. There is thus a strong potential for dust forcing to exacerbate drought during the Dust Bowl [e.g., *Koven*, 2006]. Here we investigate the contribution of SST and dust radiative forcing to the 1930s Dust Bowl drought, using a state of the art atmosphere general circulation model coupled to a dust emission and transport model. We consider the effects of SST forcing alone, and the influence of SST in combination with dust radiative forcing.

2. Models

[4] The Goddard Institute for Space Studies (GISS) ModelE is a state of the art atmospheric general circulation model, incorporating significant updates to the physics compared to previous versions, and capable of calculating the evolution of several aerosol and chemical tracers as a function of the model climate [*Schmidt et al.*, 2006; *Shindell et al.*, 2007]. Simulations of modern day climate in ModelE compare favorably with observations, with some notable biases, particularly in the subtropical marine stratocumulus regions. ModelE is unusually successful at simulating the observed annual cycle of precipitation over the Great Plains and Mexico, along with interannual variations in precipitation during the second half of the 20th century [*Ruiz-Barradas and Nigam*, 2006]. We use a version of ModelE coupled to a model of mineral dust aerosols [*Miller et al.*, 2006]. Given "natural" dust sources (i.e., excluding sources created by anthropgenic land degradation [*Ginoux et al.*, 2001]) and forced by present day ModelE climate, the dust model reproduces (within the range of observational uncer-

[1]Lamont-Doherty Earth Observatory, Ocean and Climate Physics, Palisades, New York, USA.

[2]NASA Goddard Institute for Space Studies, New York, New York, USA.

0094-8276/08/2008GL033486$05.00

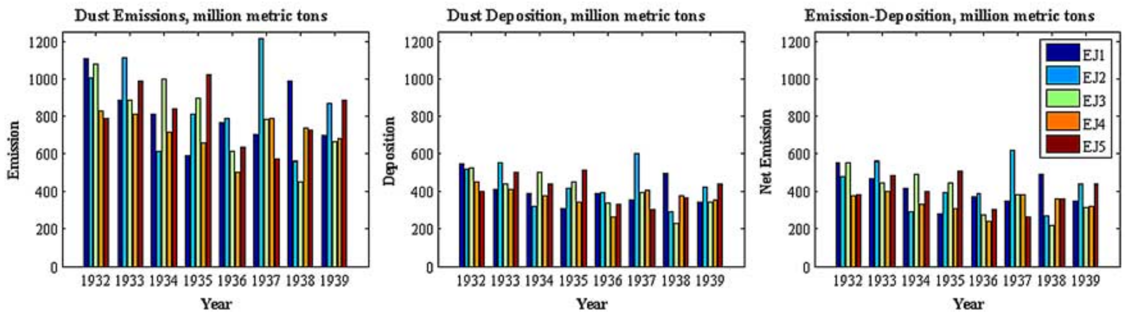

Figure 1. Net dust emissions (emission-deposition) for the Dust Bowl source region (34°N-48°N, 102.5°W-92.5°W), for each member of the SST+Dust ensemble. EJ1, EJ2, etc., refer to individual ensemble members, each with a unique initial condition.

tainty) the seasonal atmospheric dust cycle, as well as the magnitude and pattern of atmospheric dust loading [*Cakmur et al.*, 2006; *Miller et al.*, 2006]. Dust within the model interacts with radiation in ModelE (absorbing, emitting, and reflecting longwave and shortwave), but does not impact cloud microphysics.

3. Experimental Setup

[5] We conduct three sets of experiments comprised of five member ensemble model runs, with each member of the ensemble starting from a different initial condition. As a control experiment, ModelE is run with observed SSTs for the period 1920-1929 and without dust (Experiment 1). To examine SST forcing of the Dust Bowl drought, we then force the model with observed SSTs for 1932-1939, again without dust (Experiment 2). For our final experiment, we examine the combined impact of SST and dust forcing on the Dust Bowl drought by forcing the model with SSTs for 1932-1939 and active dust emission over the Great Plains (Experiment 3). Dust sources within the model are defined according to *Ginoux et al.* [2001] and correspond to topographic lows with bare ground, areas likely to accumulate sediment over geologic timescales (i.e., natural sources). This definition excludes additional dust sources created by anthropogenic disturbance. To simulate wind erosion and atmospheric dust loading during the Dust Bowl, we add a dust source over the Great Plains, over the approximate region of significant wind erosion (Figure 2, 34°N-48°N, 102.5°W-92.5°W [*Hansen and Libecap*, 2004]). Emission as a function of wind speed is scaled so that the dust cycle from natural sources generally agrees with a worldwide array of observations [*Cakmur et al.*, 2006]. However, sources created by land degradation are expected to be initially more vulnerable to wind erosion, resulting in greater emission compared to natural sources [e.g., *Tegen et al.*, 1996; *Mahowald et al.*, 2002; *Yoshioka et al.*, 2005]. We specify the disturbed sources over the Great Plains to be three times more productive compared to natural sources for a given wind event. We experimented with a range of dust source magnitudes and found emissions over the region scaled roughly linearly with the size of the specified Great Plains dust source. While the precise expansion and productivity of dust sources due to land degradation is not known, we try to constrain this below by comparing the additional dust emission by agricultural sources to estimates of observed soil loss during the Dust Bowl.

4. Results and Discussion

[6] Figure 1 shows dust emission from the land surface, dust deposition to the surface, and net dust emission (emission minus deposition) from our Experiment 3 (SST+Dust) for 1932–1939, for the region of the imposed anthropogenic dust source. Consistent with observations, dust emissions and loading are highest in the spring (March-May) period (not shown). Figure 2 outlines the area of the new dust source and the additional atmospheric dust loading in Experiment 3 (SST+Dust minus SST Only). Quantifying observations of both dust emission and atmospheric dust loading during the 1930s is difficult. While there is much anecdotal and qualitative evidence for high dust emission and atmospheric concentrations, few hard numbers are available. One estimate for 1935 alone puts the loss of topsoil to wind erosion at roughly 771 million metric tons [*Hansen and Libecap*, 2004; *Johnson*, 1947]. Net dust emission from the model for 1935 is of the same order of magnitude, but only about half of the 771 million metric

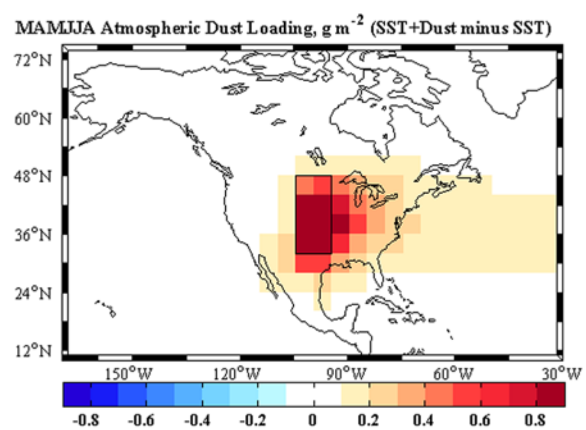

Figure 2. Ensemble mean differences in total atmospheric dust loading, g m^{-2}, Experiment 3 (SST+Dust) minus Experiment 2 (SST only). Outlined are the eight grid boxes that constitute the new dust source in the SST+Dust experiments.

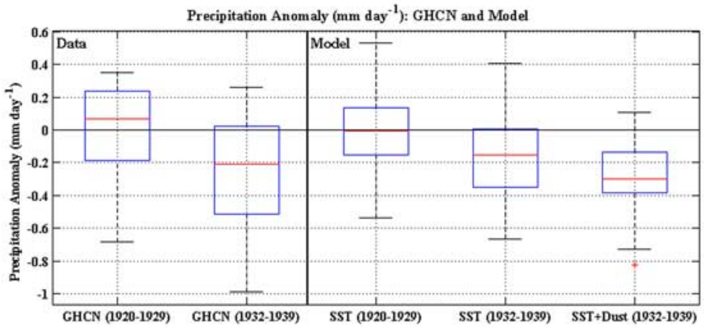

Figure 3. Box and whisker plots for precipitation anomalies, averaged over the central United States (30°N-48°N, 105°W-85°W). Shown are data from the GHCN dataset and output from the three ModelE experiments: SST forcing (1920–1929), SST forcing (1932–1939), and SST+Dust forcing (1932–1939). For GHCN data, anomalies are relative to GHCN data for 1920–1929. For model experiments, anomalies are relative to the SST forcing (1920–1929) experiment. Plots for the GHCN anomalies are based on 10 years (1920–1929) and 8 years (1932–1939); for the model output, each plot represents output from five member ensembles simulations; 50 years for 1920–1929 and 40 years for 1932–1939.

tons needed to match observations. A comparison between atmospheric dust loading from this experiment (Figure 2) and more qualitative dust storm maps from the period (not shown [*Mattice*, 1935b]) suggests that the spatial pattern of atmospheric loading is reasonable. For the moment, we note that the productivity of disturbed sources compared to natural ones is a fundamental uncertainty that can be resolved only with more definitive observations of the aerosol load and soil erosion during the Dust Bowl.

[7] We focus on spring and summer precipitation anomalies (March through August). Figure 3 shows box and whisker plots of precipitation anomalies from the GHCN precipitation dataset [*Vose et al.*, 1992] and our model experiments, averaged over the central US, the center of action for the Dust Bowl drought (30°N–48°N, 105°W–85°W). All anomalies (for the model and GHCN data) are relative to the 1920–1929 average, a period of fairly wet conditions over the US. The model, forced with 1932–1939 SSTs alone, produces a drying as seen in the GHCN data, with a reduced magnitude. Nonetheless, ~71% of the total of 40 simulated years within the 5 ensemble members were drier than the ensemble mean for the 1920s simulation. When dust forcing is included with the SST forcing, the drought intensifies, as seen in the overall shift of the distribution towards negative precipitation anomalies. The spatial pattern and intensity of the drought also changes with the inclusion of dust (Figure 4). SST forcing alone leads to fairly muted precipitation anomalies in the central plains; the resulting pattern is not dry enough and the drought extends much too far south into northern Mexico. With SST+Dust forcing, the drought intensifies and the center of drying moves north and east. Several notable differences between model and observations remain. In the model, the center of drought is shifted too far to the northeast, leading to a Great Lakes region that is too dry. The drought also does not extend far enough north, into the central Canadian plains. Parts of Mexico still show a dry anomaly, contrary to the GHCN dataset that actually shows a wet anomaly over much of Mexico. The intensity of the precipitation anomalies varied with the magnitude of our dust source, but the spatial pattern remained essentially unchanged (not shown). As with other studies, our model is unable to reproduce the large warming during the drought (not shown). It remains unclear how much of the discrepancy with observations results from uncertainty in the dust sources, compared to factors not considered here. In our experiments, the mechanisms for precipitation reductions associated with increased dust loading are consistent with other studies where reduced net radiation into the surface beneath the dust layer reduces evaporation and precipitation [e.g., *Miller and Tegen*, 1998; *Yoshioka et al.*, 2007]. We subtract (using the ensemble mean results) SST forcing from the SST+Dust forcing experiments to examine the added effect of dust. Increased atmospheric dust loading in the SST+Dust case (Figure 2) leads to reductions in net surface radiation (auxiliary material[1] Figure S1), centered under the region of highest atmospheric dust loading. Reductions in surface radiation drive reductions in surface evaporation and latent heating (auxiliary material Figure S2), leading to a negative precipitation feedback. Evaporative and soil moisture feedbacks during the Dust Bowl drought are supported by a previous study (Schubert et al., 2004).

5. Conclusions

[8] Within GISS ModelE, SST forcing alone reproduces the drought during the 1930s, but one that is too weak and centered too far to the south. By adding in a dust source over the main region of dust emission during this period, the model generates a more intense drought that has a modestly more realistic spatial pattern. For this study we did not consider other potential feedbacks (e.g., vegetation) that may have influenced the drought. These results support the notion that wind erosion and atmospheric dust concentrations that were unprecedented in the historical record could have acted as a positive feedback to drought during the Dust Bowl and potentially contributed to it being centered further to the north than typical tropical SST-forced droughts [*Seager et al.*, 2008]. It is still possible the drought resulted from SST forcing and internal variability. Large model ensembles include individual ensemble members that bear

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL033486.

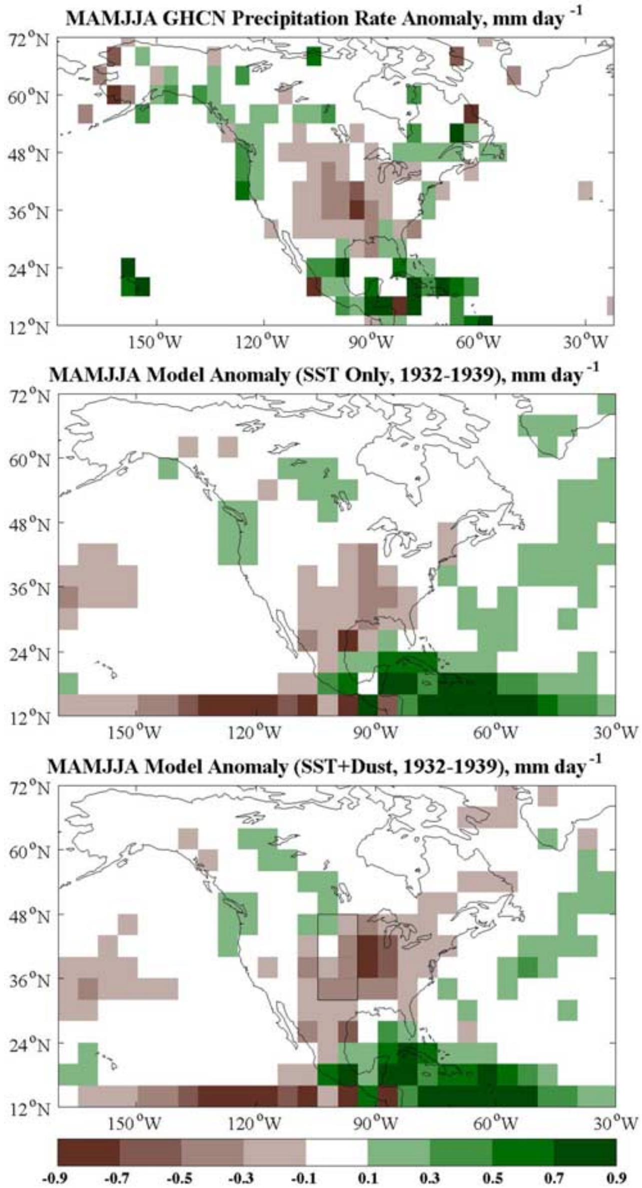

Figure 4. Spatial extent and magnitude of precipitation anomalies. Anomalies are relative to the same reference period in Figure 3.

a closer resemblance to the Dust Bowl drought, even with SST forcing only [*Schubert et al.*, 2004a; S. Schubert, personal communication, 2008]. These patterns, however, disappear in the ensemble averages.

[9] Results here are preliminary, and serve as a starting point for future work. The dust emission and source productivity, for example, should be better constrained. Indeed, the balance of evidence suggests that the modeled dust emission is smaller than what actually occurred and, hence, the results presented here may underestimate the impacts of Dust Bowl wind erosion. Thus, our study identifies the quantitative calculation of net soil loss and the pattern of the aerosol burden resulting from disturbed sources as key prerequisites for understanding the singular magnitude of the Dust Bowl.

[10] **Acknowledgments.** We thank Tom Gill, Greg Okin, and Jan Perlwitz for helpful discussions. This work is supported by the NOAA Global Change Postdoctoral Program (BIC) and the Climate Dynamics Program of the National Science Foundation through ATM-06-20066. R.L.M. also received support from the NASA Atmospheric Composition Program and R.S. was supported by NOAA grants NA06OAR4310151 and NA03OAR4320179. This paper is LDEO contribution 7150.

References

Cakmur, R. V., R. L. Miller, J. Perlwitz, I. V. Geogdzhayev, P. Ginoux, D. Koch, K. E. Kohfeld, I. Tegen, and C. S. Zender (2006), Constraining the magnitude of the global dust cycle by minimizing the difference between a model and observations, *J. Geophys. Res.*, *111*, D06207, doi:10.1029/2005JD005791.

Ginoux, P., M. Chin, I. Tegen, J. M. Prospero, B. Holben, O. Dubovik, and S.-J. Lin (2001), Sources and distributions of dust aerosols simulated with the GOCART model, *J. Geophys. Res.*, *106*(D17), 20,255–20,273.

Hansen, Z. K., and G. D. Libecap (2004), Small farms, externalities, and the Dust Bowl of the 1930s, *J. Polit. Econ.*, *112*, 665–694.

Herweijer, C., R. Seager, and E. R. Cook (2006), North American droughts of the mid to latest nineteenth century: History, simulation, and implications for medieval drought, *Holocene*, *16*, 159–171.

Hoerling, M. P., and A. Kumar (2003), The perfect ocean for drought, *Science*, *299*, 691–694.

Johnson, V. (1947), *Heaven's Tableland: The Dust Bowl Story*, Farrar, Straus, New York.

Koven, C. D. (2006), On the sources, composition, and climatic effects of mineral dust in the atmosphere, Ph.D. dissertation, Univ. of Calif., Berkeley.

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*(D21), 4561, doi:10.1029/2002JD002097.

Mattice, W. A. (1935a), Dust storms, November 1933 to May 1934, *Mon. Weather Rev.*, *63*,53–55.

Mattice, W. A. (1935b), Dust storms, *Mon. Weather Rev.*, *63*, 113–115.

Miller, R. L., and I. Tegen (1998), Climate response to soil dust aerosols, *J. Clim.*, *11*, 3247–3267.

Miller, R. L., et al. (2006), Mineral dust aerosols in the NASA Goddard Institute for Space Sciences ModelE atmospheric general circulation model, *J. Geophys. Res.*, *111*, D06208, doi:10.1029/2005JD005796.

Rosenfeld, D., Y. Rudich, and R. Lahav (2001), Desert dust suppressing precipitation: A possible desertification feedback loop, *Proc. Natl. Acad. Sci. U.S.A.*, *98*, 5975–5980.

Ruiz-Barradas, A., and S. Nigam (2006), IPCC's twentieth-century climate simulations: Varied representations of North American hydroclimate, *J. Clim.*, *19*, 4041–4058.

Schmidt, G. A., et al. (2006), Present-day atmospheric simulation using GISS ModelE: Comparison to in situ, satellite, and reanalysis data, *J. Clim.*, *19*, 153–192.

Schubert, S. D., M. J. Suarez, P. J. Region, R. D. Koster, and J. T. Bacmeister (2004a), On the cause of the 1930s Dust Bowl, *Science*, *303*, 1855–1859.

Schubert, S. D., M. J. Suarez, P. J. Region, R. D. Koster, and J. T. Bacmeister (2004b), Causes of long-term drought in the United States Great Plains, *J. Clim.*, *17*, 485–503.

Seager, R. (2007), The turn of the century North American drought: Global context, dynamics, and past analogs, *J. Clim.*, *20*, 5527–5552.

Seager, R., N. Harnik, W. A. Robinson, Y. Kushnir, M. Ting, H. P. Huang, and J. Velez (2005a), Mechanisms of ENSO-forcing of hemispherically symmetric precipitation variability, *Q. J. R. Meteorol. Soc.*, *131*, 1501–1527.

Seager, R., Y. Kushnir, C. Herweijer, N. Naik, and J. Velez (2005b), Modeling of tropical forcing of persistent droughts and pluvials over western North America: 1856–2000, *J. Clim.*, *18*, 4068–4091.

Seager, R., Y. Kushnir, M. Ting, M. Cane, N. Naik, and J. Miller (2008), Would advance knowledge of 1930s SSTs have allowed prediction of the Dust Bowl drought?, *J. Clim.*, in press.

Shindell, D. T., G. Faluvegi, S. E. Bauer, D. Koch, N. Unger, S. Menon, R. L. Miller, G. A. Schmidt, and D. G. Streets (2007), Climate response to projected changes in short-lived species under the A1B scenario from 2000–2050 in the GISS climate model, *J. Geophys. Res.*, *112*, D20103, doi:10.1029/2007JD008753.

Tegen, I., A. A. Lacis, and I. Fung (1996), The influence on climate forcing of mineral aerosols from disturbed soils, *Nature*, *380*, 419–422.

Vose, R. S., L. Richard, P. M. Schmoyer, T. C. Steurer, R. H. Peterson, K. R. Thomas, and J. Eischeid (1992), The global historical climatology network: Long-term monthly temperature, precipitation, sea level pressure, and station pressure data, *Rep. ORNL/CDIAC-53, NDP-041*, Carbon Dioxide Inf. Anal. Cent., Oak Ridge Natl. Lab., Oak Ridge, Tenn.

Worster, D. (1979), *Dust Bowl: The Southern Plains in the 1930s*, 277 pp., Oxford Univ. Press, New York.
Yoshioka, M., N. Mahowald, J.-L. Dufresne, and C. Luo (2005), Simulation of absorbing aerosol indices for African dust, *J. Geophys. Res.*, *110*, D18S17, doi:10.1029/2004JD005276.
Yoshioka, M., N. Mahowald, A. J. Conley, W. D. Collins, D. W. Fillmore, C. S. Zender, and D. B. Coleman (2007), Impact of desert dust radiative forcing on Sahel precipitation: Relative importance of dust compared to sea surface temperature variations, vegetation changes, and greenhouse gas warming, *J. Clim.*, *20*, 1445–1467, doi:10.1175/JCL14056.1.

R. Seager, Lamont-Doherty Earth Observatory, Ocean and Climate Physics, 61 Route 9W, P.O. Box 1000, Palisades, NY 10964-8000, USA. (bc9z@ldeo.columbia.edu)
B. I. Cook and R. L. Miller, NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA.