be inflated by the amount of $NO_3^-$ N leached to the subsoil; the latter is substantial at some of the sites investigated. Averaged over $Cl^-$-based accumulation times, long-term $NO_3^-$ N soil losses via leaching to the subsoil reservoir range from $3 \times 10^{-3}$ to $6.8 \times 10^0$ kg of N $ha^{-1}$ $year^{-1}$ (table S2). For comparison, mean annual inorganic N in wet deposition ($NO_3^-$ N plus $NH_4^+$-N) ranges from 0.8 to 4 kg of N $ha^{-1}$ $year^{-1}$ in the western half of the United States (*20*). Our data do not permit precise generalization of $NO_3^-$ N soil leaching to subsoil reservoirs. Even so, $NO_3^-$ N soil leaching clearly constitutes an appreciable fraction of atmospheric N deposition over large areas.

Leaching of N from arid soil zones is unexpected, given the N-limited nature of desert ecosystems and the high nutrient utilization efficiency of xeric plants (*10*, *21*, *22*), and cannot be readily explained. The presence of large quantities of $NO_3^-$ N sequestered below a depth of 1 m demonstrates that not all of the available $NO_3^-$ N is consumed in the soil zone or returned to the atmosphere. Ecologic implications follow, given the strong linkages between nutrient cycling and plant community dynamics. Recent studies show that desert plants do not necessarily take up water and nutrients simultaneously (*23*). In addition, some species may rely solely on available N at the soil surface (*24*). Such behaviors may help explain the apparent paradox of $NO_3^-$ N leaching from soils populated by N-limited vegetation.

Subsoil $NO_3^-$ reservoirs also have implications for groundwater quality, as their mobilization may adversely affect public water supplies. Drinking water exceeding the maximum contaminant level established by the U.S. Environmental Protection Agency of 10 mg of $NO_3^-$ N $liter^{-1}$ is associated with methaemoglobinaemia, miscarriages, and non-Hodgkin's lymphoma (*3*, *25*). Investigations in the 1970s reported large amounts of subsoil $NO_3^-$ in southern California (*26*) and central Nebraska (*27*) that could not be attributed to agriculture or other human activities. Similarly, investigations of high $NO_3^-$ levels in Las Vegas Valley groundwater near irrigated fields ruled out fertilizer, livestock, and septic systems as sources of pollution (*28*). Recent studies indicate that subsoil $NO_3^-$ reservoirs are readily mobilized to groundwater when desert land is converted to irrigation (*29*) (fig. S3). Dam construction or changes in climate and vegetation could likewise mobilize subsoil nitrate reservoirs, with local to regional effects.

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Figs. S1 to S3
Tables S1 and S2
References

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# African Droughts and Dust Transport to the Caribbean: Climate Change Implications

**Joseph M. Prospero[1]* and Peter J. Lamb[2]**

**Great quantities of African dust are carried over large areas of the Atlantic and to the Caribbean during much of the year. Measurements made from 1965 to 1998 in Barbados trade winds show large interannual changes that are highly anticorrelated with rainfall in the Soudano-Sahel, a region that has suffered varying degrees of drought since 1970. Regression estimates based on long-term rainfall data suggest that dust concentrations were sharply lower during much of the 20th century before 1970, when rainfall was more normal. Because of the great sensitivity of dust emissions to climate, future changes in climate could result in large changes in emissions from African and other arid regions that, in turn, could lead to impacts on climate over large areas.**

Aerosols, including mineral dust, can affect climate directly by scattering and absorbing solar radiation and indirectly by modifying cloud physical and radiative properties and precipitation processes (*1*). Over large areas of the Earth, the atmospheric aerosol composition is dominated by mineral dust. Dust storms and dust plumes are the most prominent, persistent, and widespread aerosol features visible in satellite images (*2*). Dense dust hazes often cover huge areas of the Atlantic, Pacific, and Indian oceans down-

wind of sources in arid regions in Africa, Asia, and the Middle East (*3*).

The recent Intergovernmental Panel on Climate Change (IPCC) assessment (*4*) concludes that dust could be playing an important role in climate forcing. In arriving at forcing estimates over recent Earth history, the IPCC assumes that natural dust sources have been effectively constant over the past several hundred years and that all variability is attributable to human land-use impacts, which they estimate to contribute 20 to 50% of total present-day dust emissions. There is little firm evidence to support either of these assumptions. Thus, in order to understand the forcings involved in past climate trends and to improve estimates of future dust-related forcings, it is necessary to characterize the variability of dust emissions in response to climate-change scenarios and to distinguish between natural processes and human impacts. In this report, we present long-term measurements of soil dust carried by easterly trade winds from sources in North Africa to the Caribbean. We relate this variability to climate variability in North Africa as manifested in rainfall.

We have measured trade-wind aerosols at Barbados (13°10′N, 59°30′W) almost continuously since 1965 at a site on the easternmost coast of the island (*5*, *6*). We draw air through filters during on-shore wind conditions, extract the soluble materials, ash the filter, and weigh the mineral residue, which we subsequently ascribe to mineral dust (*6*–*8*). During much of the year, and especially during the summer, winds carry large quantities of dust, often producing dense hazes throughout the tropical Atlantic and Caribbean (*5*, *6*).

The Barbados annual dust cycle is linked to the cycle of dust activity in North Africa and to seasonal changes in large-scale atmospheric circulation patterns (*3*). During summer, satellite images show dust outbreaks that emerge from the west coast of Africa, 4500 km east of Barbados, in pulses every 3 to 5 days, following behind easterly waves. About a week later, dust arrives in the Caribbean (*6*) and the southeast United States (*7*, *9*). Although there is much dust activity in Africa in winter, transport is mainly in latitudes south of Barbados (*3*), carrying dust into South America.

The strong annual dust cycle with its June-July maximum stands out clearly throughout our entire record over the period 1965 to 1998 (Fig. 1). Large changes are also evident from year to year and over the longer term. Concentrations were low in the mid- to late 1960s but increased sharply in the early 1970s, and they have remained relatively high thereafter. The increase in the 1970s is associated with the onset of drought in the Soudano-Sahel (SS), an arid region south of the Sahara between 11°N and 18°N that has a history of long-term wet and dry phases (*10*, *11*).

A scatter plot of Barbados mean May-to-September dust loads against prior-year precipitation in the SS, as measured by the SS precipitation index (SSPI) (*11*), shows a strong anticorrelation (Fig. 2). The plot yields the regression

$$y = -9.77x + 12.80 \qquad (1)$$

where $y$ is the dust concentration and $x$ is the SSPI value (supporting online text). The correlation coefficient $r$ is high, 0.75 ($P < 0.001$). Scatter plots of dust against current-year SSPI values (Fig. 2) yield a weaker correlation, whereas that against the following-year SSPI yields no correlation. Similar scatter plots against rainfall data for other regions in West Africa (*12*) yield poorer or no correlations.

The strong correlation of dust with rainfall deficits does not necessarily mean that rainfall itself (or the lack of it) is the dominant mechanism responsible for the correlation. Dust concentrations in Barbados are the end result of many processes, including variations in dust emissions in the source regions, changes in dust transport paths, and changes in removal during transit, especially by precipitation. Changes in meteorology in the source regions (e.g., wind speed or gustiness) associated with large-scale climate variability could play a major role (*13*). Indeed, most

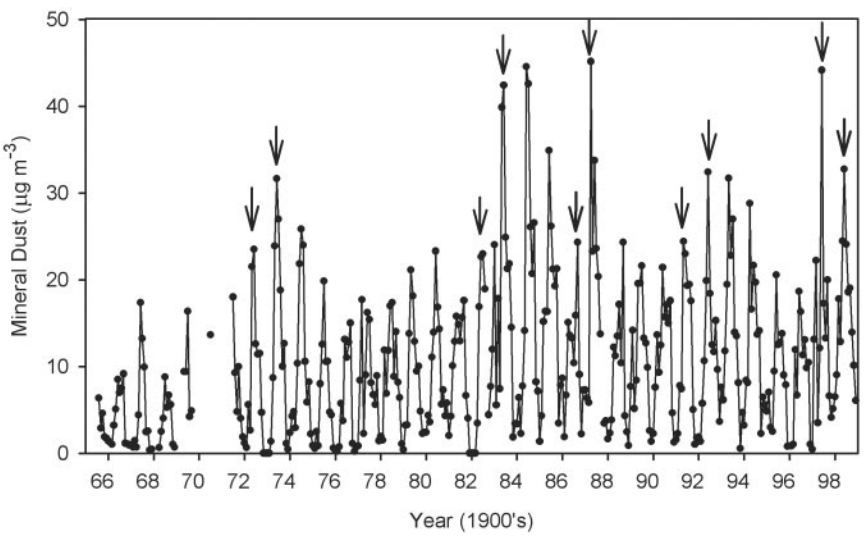


**Fig. 1.** Monthly mean dust concentrations on Barbados from 1965 to 1998. Units: $\mu g\ m^{-3}$. Arrows indicate the years when a major ENSO event occurred: 1972–73, 1982–83, 1986–87, 1991–92, and 1997–98 (*39*).

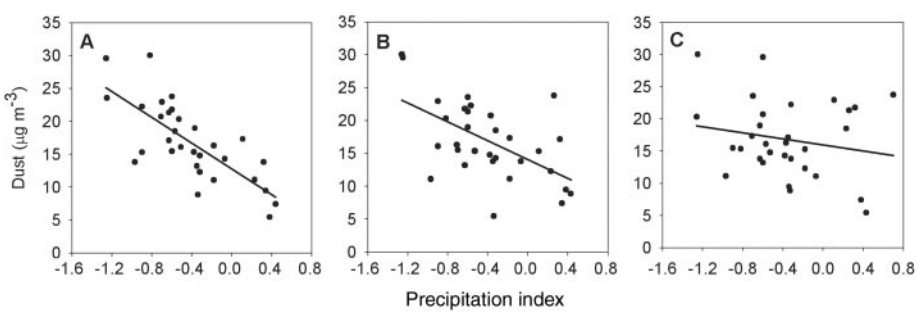


**Fig. 2.** Scatter plots of Barbados May-to-September mean dust loads against the SSPI (*11*) updated (supporting online text) and normalized to the period 1941 to 2001. (**A**) Dust plotted against the prior-year SSPI. (**B**) Dust against the current-year SSPI. (**C**) Dust against the following-year SSPI. SSPI is measured in normalized departures (standard deviations) from the long-term mean. Linear regression equations and coefficients of determination are (A) $y = -9.77x + 12.80$, $r = 0.75$ ($P < 0.001$); (B) $y = -7.18x + 14.05$, $r = 0.57$ ($P < 0.001$); and (C) $y = -2.36x + 16.00$, $r = 0.192$ ($P = 0.30$). The scatter plot of dust against the following-year SSPI suggests that the correlations are not spurious. A similar series of scatter plots of winter mean dust concentrations against the SSPI (*11*) (supporting online text) yields no significant correlations.

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major dust peaks (Fig. 1) appear to be associated with major El Niño events, which lead the dust peak by 1 year. Deficient SS rainy seasons have been linked to El Niño–Southern Oscillation (ENSO) events (*14*) and the strength of the West African monsoon to an interhemispheric contrast in tropical Atlantic sea-surface temperature anomalies (*11*, *15*). Trends in Barbados dustiness have also been associated with changes in the North Atlantic Oscillation (*16*, *17*), although the correlation is much weaker than that with rainfall presented here.

Although we cannot quantify the relative importance of these various processes in controlling transport, the trends that we observe in Barbados are consistent with a general increase in dustiness in North Africa and a corresponding widespread long-term decrease in visibility (*18*). In Mauritania, a major dust source region in West Africa (*19*), the frequency of dust storms has increased sharply in recent decades (*20*) and is inversely correlated with prior-year rainfall. Satellite records of dust concentration are only available starting in the 1980s, but these also show as interannual variability inversely related to prior-year rainfall (*21*).

The interpretation of the Barbados dust record in terms of climate processes is complicated by the possible role of humans in dust mobilization. In regions of marginal rainfall, agriculture and grazing livestock disturb soils and natural vegetation, so that wind erosion can become severe during drought (*22*), as in the U.S. Dust Bowl in the 1930s. In the SS, population has grown markedly, by a factor of ~3, between 1950 and 1995 (*23*), although much of this growth has been in urban areas. Increased population, along with the introduction of cash crops and vastly increased herds of livestock, have resulted in destabilized soils in many regions and raised concerns about desertification (*24*).

Although human impacts are clearly evident in many regions, they do not appear to play a major role in large-scale dust mobilization in North Africa, where the largest dust sources lie on the dry side of the 200- to 300-mm isohyets (*19*, *21*, *25*). Agricultural and grazing activities can be supported in such regions, but they are confined to areas around point sources of water. Consequently, land degradation is limited to relatively small areas. Most agricultural and grazing activity takes place south of the 200- to 300-mm isohyets. Indeed the strongest, largest, and most persistent dust sources in North Africa are in regions that are essentially uninhabited (*19*, *21*).

Estimates of the present-day transport of dust on global scales suggest that North Africa is by far the largest single source (*26*). However, North Africa has been unusually dry over the past 30 years (*11*) (supporting online text). We asked the question: How much dust was transported under more normal precipitation conditions? To address this issue, we estimated the longer-term May-to-September dust trends at Barbados using Eq. 1 and the SSPI for the period 1941 to 1998 (*12*) (supporting online text). Our estimates (Fig. 3) yielded sharply lower dust concentrations in the recent past. During the 1950s, when SS rainfall was relatively plentiful, the estimated mean May-to-September Barbados dust load would have been ~5 μg $m^{-3}$. The mean during the 1980s, when drought was most intense, was about four times greater, 19 μg $m^{-3}$. In the reconstructed dust record between 1941 and 1998, the years yielding the 10 lowest May-to-September estimated mean concentrations all occurred before 1966, and their mean was 3.0 μg $m^{-3}$; in contrast, the 10 highest means occurred after 1972 and their mean, 21.4 μg $m^{-3}$, was seven times greater.

This great increase in dust activity complicates the assessment of climate forcing, which normally focuses on greenhouse gases and anthropogenic aerosols, usually sulfate (*27*), and their time trends. $SO_2$ emissions from Europe and North America (*28*, *29*) approximately doubled from the 1940s to the 1980s, when they started to decrease. Overall, the increase in African dust emissions and transport over this period appears to have been much greater than that of anthropogenic aerosols from North America and Europe. Because African dust sources account for about half the global total in recent times (*26*), the low rate of African emissions in the 1940s and 1950s suggests that the global dust burden could have been about two-thirds that of recent decades, all other dust emissions being constant. Indeed, longer-term African precipitation data (*30*) show that the extended period of drought beginning in the late 1960s was unprecedented in the 20th century. Thus, the intense dust transport observed in recent decades may have been an anomaly in the past century.

The great variability in dust transport demonstrates the sensitivity of dust mobilization to changes in regional climate and highlights the need to understand how dust, in turn, might affect climate processes on larger scales. Many aspects of the radiative properties of dust are still open to question (*1*, *31*). Nonetheless, dense dust clouds over the oceans reduce insolation at the ocean surface, thereby reducing the heating of ocean surface waters (*32*) and sea-surface temperatures, which in turn affects the ocean-atmosphere transfer of water vapor and latent heat, which are important factors in climate (*28*). Reduced heating over the tropical Atlantic could contribute to the interhemispheric, tropical Atlantic, sea-surface temperature anomaly patterns that have been associated with SS drought (*11*, *15*). Thus, increased dust could conceivably lead to more intense or more prolonged drought. Also, the frequency and intensity of Atlantic hurricanes have been linked to West African rainfall (*33*), showing decreased activity during dry phases.

Dust could also affect climate through cloud microphysical processes, possibly suppressing rainfall and conceivably leading to the perpetuation and propagation of drought (*34*). Over south Florida, clouds are observed

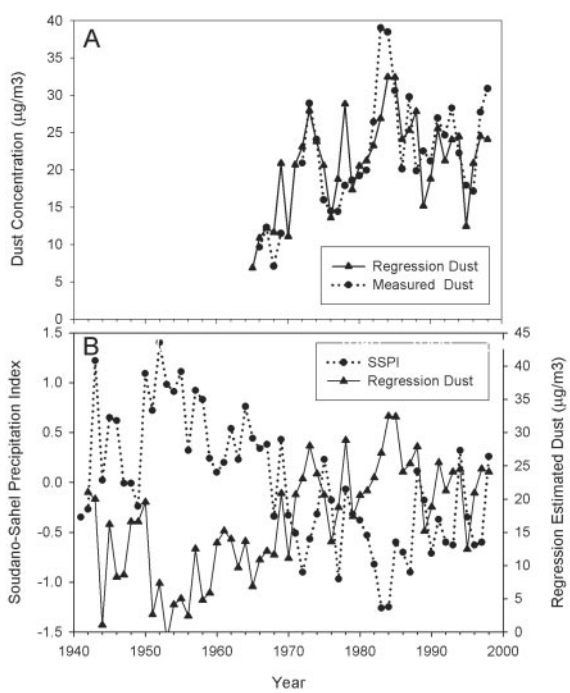


**Fig. 3.** Mean May-to-September dust concentrations on Barbados, 1941 to 1998, back-calculated against the SSPI with the regression equation $y = -9.77x + 12.8$, where $x$ is the SSPI. **(A)** Regressed dust concentrations compared to measured dust concentrations. **(B)** Regression dust concentrations compared to the long-term SSPI. The good agreement between the measured and calculated concentrations from 1965 to 1998 in Fig. 3A lends confidence to the back-calculated concentrations to 1941 in Fig. 3B.

to glaciate at relatively warm temperatures in the presence of African dust (*35*), an effect that could alter cloud radiative processes, precipitation, and cloud lifetimes.

The great variability of African dust transport has broader implications beyond weather and climate. Iron associated with dust is an important micronutrient for phytoplankton (*36*). Thus, variations in dust transport to the oceans could modulate ocean primary productivity and, consequently, the ocean carbon cycle and atmospheric $CO_2$. Certain species of cyanobacteria also use iron in their metabolism; the rate of production of nitrate, a primary nutrient, by these organisms could be strongly influenced by dust inputs (*36*, *37*).

Finally, during intense drought phases, the concentration of respirable dust (*38*) over the Caribbean probably exceeds the U.S. Environmental Protection Agency's 24-hour standard. Although there is no evidence that exposure to dust across this region presents a health problem, it does demonstrate how climate processes can bring about changes in our environment that could have a wide range of consequences on intercontinental scales.

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# Oceanic Forcing of Sahel Rainfall on Interannual to Interdecadal Time Scales

**A. Giannini,[1]*† R. Saravanan,[1] P. Chang[2]**

**We present evidence, based on an ensemble of integrations with NSIPP1 (version 1 of the atmospheric general circulation model developed at NASA's Goddard Space Flight Center in the framework of the Seasonal-to-Interannual Prediction Project) forced only by the observed record of sea surface temperature from 1930 to 2000, to suggest that variability of rainfall in the Sahel results from the response of the African summer monsoon to oceanic forcing, amplified by land-atmosphere interaction. The recent drying trend in the semi-arid Sahel is attributed to warmer-than-average low-latitude waters around Africa, which, by favoring the establishment of deep convection over the ocean, weaken the continental convergence associated with the monsoon and engender widespread drought from Senegal to Ethiopia.**

The cause of the persistence of drought in the African Sahel during the 1970s and 1980s (*1*) has yet to be determined. Is human activity to blame, or is climate variability an issue that the newly independent nations of sub-Saharan Africa would have to contend with as they devised strategies for their development (*2*)?

Over the past 30 years, research into the physical cause(s) of the recurrence of drought in Africa has progressed along two parallel directions. One, motivated by the belief that humanity was irreversibly impacting the environment and climate—by way of land cover and/or land use changes associated with the expansion of farming and herding into marginal areas, ultimately linked to the pressure of rapid population growth—emphasized the role of the feedback between the atmospheric circulation and land surface processes. The other, revitalized by the initial successes in dynamical seasonal prediction of the mid-1980s, pointed to the atmospheric response to temperature changes in the global oceans as the leading cause of African climate variability.

Charney's influential work on the positive albedo-precipitation feedback (*3*, *4*) pointed to the potential relevance of land surface conditions in the prolonged Sahel drought; an increase in surface albedo due to a human-induced change in vegetation cover could cause a decrease in precipitation that, in turn, would lead to a decrease in vegetation cover and thus a further enhancement of the albedo. What has become popularly known as "Charney's hypothesis" has, through the years, engendered a number of modeling studies of increasing detail (*5*–*7*). Although these studies generally support a land surface feedback mechanism, the extent to which this mechanism constitutes the leading cause of African climate variability has not been established, in part because the prescribed changes in land surface and/or vegetation cover were largely ex-

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