Indirect climate forcing over the western US from Asian dust storms

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1 Aerosols lofted to high altitudes by springtime Asian dust storms advect across the Pacific Ocean and, as recognized in recent years, regularly reach the western US. As part of our long-term cirrus cloud research program using remote sensing measurements, we have observed unusually warm cirrus ice clouds associated with transported Asian dust aerosols. The polarization lidar data presented for illustration here suggest that the dust particles, which are indicated to be especially active ice nuclei, can affect the formation and phase of clouds, and hence alter their radiative properties at least as far away as the eastern Great Basin of the US.

INDEX TERMS: 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 0305 Atmospheric Composition and Structure: Aerosols and particles (0345 4801); 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 9320 Information Related to Geographic Region: Asia

1. Introduction

The often significant local effects of winter and spring dust storms that are spawned over the elevated Gobi and Mongolian deserts have historically been well documented in China, Japan, and Korea [Iwasaka et al., 1983]. Evidence has accumulated that the long-range transport of Asian dust across the Pacific Ocean has left its mark on the soils of Hawaii [Biscaye et al., 1997] and the ice sheet of Greenland [Rex et al., 1969]. It has also recently been realized that the transport of the dust storm debris can even impact North American air quality [Husar et al., 2001]. Over the past few years since the major April 1998 Asian dust storm events, a variety of international research programs using advanced instruments have been applied to monitoring the consequences of the dust storms. The tools involve a growing array of aerosol lidar sites combined with advanced satellite-based measurements and aerosol transport models that track the path of the dust clouds over extended distances. From this increased scientific scrutiny it is clear that the direct climatic effects of Asian dust storms extend over a wide geographic region of the Northern Hemisphere. It is also of considerable interest whether current agricultural activities in the worlds desert regions, or other climatic factors, are adding to the historic impact of the intensity of dust storms.

2. The FARS Dataset

Since October 1987, regular ruby (0.694 um) lidar and radiometer observations of high clouds in support of the First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment [Cox et al., 1987] have been collected from the University of Utah Facility for Atmospheric Remote Sensing [FARS, Sassen et al., 2001]. These measurements, which amount to ~200-h per year, have been directed primarily toward sampling cirrus clouds during periods corresponding to satellite overpasses for the purpose of validating the cloud properties retrieved from Earth orbit [Sassen and Campbell, 2001]. Nonetheless, the lidar data typically have sufficient dynamic range to reveal the presence of even weakly backscattered signals from aerosols from just above the surface to altitudes up to the middle and upper troposphere.

An examination of this unique dataset reveals that surface-based and elevated aerosol layers are a common feature over the eastern Great Basin of the US during the winter and spring months. During this relatively moist time of year, local aerosol sources are generally suppressed, such that distant sources are required to elevate the particles far above the surface, as is often observed. The aerosols are sometimes dense enough to cause reductions in horizontal visibility, and can resemble very thin cirrus clouds against the blue sky when occurring in dense, elevated layers. As described previously [Sassen, 2001; Sassen et al., 2001], the lidar-derived aerosol heights often correspond to the locations of dry air layers, in keeping with the concept of aeolian lifting and transport in a generally cloud- and precipitation-free environment. In many cases, the local arrival of Asian dust clouds is predicted by satellite observations and aerosol transport models, following Asian surface and lidar reports of dust storm activity [Murayama et al., 1998]. This international effort has been greatly facilitated by a “virtual” scientific community of internet-based real-time information exchanges.

Another important feature of Asian dust is the characteristic nonspherical shape of the relatively large loess (clay) particles [Okada et al., 2001], which makes them capable of generating significant amounts of laser backscatter depolarization. The lidar linear depolarization ratio δ, the ratio the backscattered powers in the planes of polarization orthogonal and parallel to that the transmitted laser pulse, is used to characterize the change in the state of backscattered laser light. Thus, lidar systems with polarization diversity have an advantage in identifying these depolarizing particles, in comparison to the small amounts of depolarization produced by spherical haze particles or minute particulates. However, nonspherical particle size also exerts an influence on lidar δ-values, because the effective diameter must be at least comparable to the incident wavelength to generate significant depolarization [Mishchenko and Sassen, 1998]. In terms of cloud research, the ability to distinguish between spherical droplets and ice crystals using backscatter depolarization is unambiguous.

In recent years the FARS data record seems to show an increasing frequency and burden of springtime aerosol layers, although since our attention was first drawn to the true nature of these dust events in 1998, we have devoted more observations to...
them even in the absence of cirrus cloud cover. In this report we concentrate on recent FARS case studies of the apparent impact of the aerosol on cloud formation and thermodynamic phase. This new aspect of the problem has the potential for climate change through indirect cloud effects on the radiation balance of the earth/atmosphere system.

3. Recent Case Studies

[8] During April 2001, a series of intense Asian dust storms drew worldwide popular and scientific attention. A particularly intense dust storm that occurred in mid-April was dubbed the “Dust Storm of the Century” because of the evidence for dust transport across the North American continent. At FARS, from mid-April into early May there were nearly continuous lidar observations of transported Asian dust layers.

[9] In Figures 1–3 we provide lidar data over about a one-day period from 29–30 April 2001 that depict conditions in which both clouds and Asian aerosols were present. In these figures are given height versus time displays of lidar relative backscattering and linear depolarization ratios, along with the nearby Salt Lake City National Weather Service sounding. The presence of the Asian aerosol is indicated by the weakly-backscattering and horizontally-stratified layers stretching from the surface up to ~9–10 km above mean sea level (MSL). Dust-dominated (i.e., over molecular) lidar depolarization is revealed at this wavelength by $\delta \approx 0.20$, although even regions with lower $\delta$ that appear to be molecular-dominated ($\delta < 0.05$) may still contain lesser aerosol amounts. In comparison, lidar backscattering and depolarization are considerably stronger in the ice clouds shown at various levels, where, on average, cirrus $\delta$ values can be expected to increase with decreasing temperature [Sassen and Benson, 2001].

[10] With the exception of the higher (10–12 km), colder (~0 to ~−50°C) cirrus clouds probed from ~1800–1930 UTC on 30 April (Figure 3), all the other ice clouds can be seen to be in contact with dust layers. Typically, the cirrus cloud top heights lie close to the diffuse tops of the aerosol layers, where more moisture may have become available for cloud formation from mixing processes during transport. The average cloud top temperatures of the lower, dust-contaminated cirrus are ~−40°C in Figure 1, −35°C in Figure 2, and −25°C in Figure 3. In comparison to the
climatological means for cirrus studied at FARS over a 10-yr period, these ice clouds are considerably warmer and lower: average cirrus for the spring months have cloud base and top heights and temperatures of 8.89 and 11.14 km and \(-38.4^\circ\)C and \(-55.3^\circ\)C, respectively \cite{Sassen and Campbell, 2001}. As a matter of fact, <2% of all cirrus studied at FARS have temperatures \(>-40^\circ\)C, and most of these correspond to sheared particle fall-streaks extending below colder cirrus, certainly not the case here.

The warmest (up to \(-20^\circ\)C) of the ice clouds in Figure 3 (at right) is particularly interesting. Visual observations indicate that this cloud resembled cirrus fibratus when overhead, but was earlier classified as a deep, water-dominated altocumulus as it approached slowly from the north. In other words, this midlevel cloud glaciated with time to produce a pure ice cloud at relatively warm temperatures. In addition, the ultimate fate of those aerosols involved in cloud formation, removal due to nucleation and scavenging, often seems to be indicated by the lower backscattering and depolarization in regions surrounding the ice clouds: note especially the relatively aerosol-free region adjacent to the cirrus cloud in the middle of Figure 2.

Nor are these unusual cloud conditions unique at FARS. A particularly interesting example occurred on 19 April 2001, when fractus-like clouds composed of ice were sampled at the top of a dust-filled convective boundary layer at \(-21^\circ\)C. The concurrent sounding indicated humidities very close to water-saturation at this level. Normally, liquid phase fractocumulus clouds would be expected to form under such conditions, but in this case the dust particles may have served as deposition nuclei and formed ice directly from the vapor in ice-supersaturated air. Such evidence indicates that the phase of clouds can be influenced by the presence of Asian dust.

4. Discussion

It is clear that, in comparison to the mean cirrus cloud macrophysical properties derived from a 10-yr FARS sample \cite{Sassen and Campbell, 2001} the properties of the low cirrus cloud layers associated with the Asian aerosol are highly unusual. With cloud top temperatures as warm as \(-20^\circ\)C, few, if any, cirrus clouds in the FARS sample had such warm temperatures. Moreover, observations of supercooled liquid altocumulus clouds with temperatures between \(-20^\circ\)C to \(-35^\circ\)C are not uncommon at our locale. Below we describe the results of laboratory research that indicate that it is the unusual ice nucleating capabilities of Asian dust particles that may be responsible for these findings.

In an early study of the concentrations of ice nuclei (IN) measured by a laboratory device that was conducted (coincidentally) during April-May 1958 from Tokyo, Japan, abnormally high IN concentrations were reported on days when Kosa (yellow) dust aerosols were present \cite{Isono et al., 1959}. At a chamber temperature of \(-20^\circ\)C, in excess of 50 IN per liter were obtained when the air mass trajectories were traced back to Asian dust storms. Such concentrations were the highest observed and significantly greater than those measured when under maritime air flow, and are now known to be comparable to typical ice crystal concentrations in many cirrus clouds. The great efficacy of some dust particles to serve as IN has been attributed to the similar crystallographic structure of clay materials such as kaolinite to that of ice. Schaller and Fukuta \cite{1979} found that this clay material had a condensation-freezing nucleation threshold of \(-9.9^\circ\)C, and a deposition threshold of \(-19.0^\circ\)C at an ice supersaturation of 20.3%. Such threshold temperatures are unusually warm for natural aerosols, and it was even suggested by Isono et al. \cite{1959} that the arid regions of the Asiatic continent could be an important world-wide source of IN.

5. Conclusions

The knowledge gained from early laboratory studies that wind-raised desert dust particles from Asia are especially effective IN has been overlooked until quite recently. Climate change issues have emphasized the direct forcings caused by increased Greenhouse gases and pollution aerosols in the atmosphere, although the more difficult problem of the indirect climatic effects of aerosols...
acting as cloud-forming particles is gaining increasing attention. The latter can include the effects of industrial pollutants, and ship and aircraft engine exhausts on cloud content, and as now coming under scrutiny, the consequences of increased biomass burning and desertification.

[16] The potential climate change mechanism considered here with the aid of polarization lidar observations involves the radiative consequences of the peculiar ice nucleating abilities of clay particles, in combination with the large-scale atmospheric dispersal of the agents via major dust storms. As indicated here and suggested elsewhere, the Asian dust aerosol appears to be effective at generating cirrus clouds at the margins of moist atmospheric layers [Sassen, 2000, 2001; Murayama et al., 2001]. Through case studies and climatologically-based comparisons, it is now also indicated that supercooled water clouds can be converted to ice clouds at moderate temperatures, say perhaps 20°C warmer than what is typical from the homogeneous nucleation of cloud droplets in the middle and upper troposphere. This results in the creation of cirrus or cirrus-like clouds at much warmer than usual temperatures, and probably in the shorter life span of supercooled water/mixed phase clouds. In one of the examples given here, a midlevel water cloud was noted from visual observations to gradually transform into an ice cloud. The phase change in this case altered the characteristic cloud particle sizes and perhaps the cloud lifetime, which is certain to modulate the radiative processes in the atmosphere. The overall climatic impact of such processes is not straightforward to evaluate, but mean water cloud reductions could decrease the planetary albedo and increase surface warming. The effects of possibly increased lower-level cirrus clouds also need to be evaluated. Radiative calculations tailored to this particular scenario are clearly needed to resolve this issue, along with an innovatory of the various global sources and amounts of desert dusts. However, if atmospheric dust transport is increasing due to our changes in land use in Asia and elsewhere, then this will represent yet another mechanism by which humans are perturbing our climate.

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References

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