Albedo reduction by absorbing aerosols over China

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[1] Long-term observations with satellites show that absorbing aerosols have reduced the local planetary albedo (LPA) over China during the recent decade. While the reduction of air pollution was leading to an LPA decrease in Europe, an increase of pollution in China also lowered the LPA. The strong absorption in clouds is accompanied by a cloud lifetime effect over the Red Basin and surrounding areas in southern China. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305). **Citation:** Krüger, O., and H. Graßl (2004), Albedo reduction by absorbing aerosols over China, *Geophys. Res. Lett.*, *31*, L02108, doi:10.1029/2003GL019111.

1. Introduction

[2] During the last two decades East Asia was the most rapidly developing area in the world. The population growth in East Asian countries and the rapid economic development are accompanied by an air pollution increase [*UNEP and C*^{4}, 2002]. The enormously increased concentration of aerosol particles leads to massively lowered visibility and also shortwave radiation reaching the surface [*Xu*, 2001].

[3] A plausible consequence would be an increased local planetary albedo (LPA) for cloudless and cloudy atmospheres. We investigated changes of LPA at $\sim$0.8 μm wavelength using AVHRR channel 2 data. The LPA here is represented by a reflectance which is calculated from the radiance at the satellite and the solar irradiance [*Rao*, 1987].

[4] Since the 1970s an effect on clouds induced by air pollution has been discussed [*Twomey*, 1974]. Theoretical studies on the basis of measurements suggested that near the source regions of pollution there are two competing processes [*Twomey et al.*, 1984]. Firstly, there is an increase of the concentration of cloud droplets via increased cloud condensation nuclei. This results – at unchanged cloud water – in a larger surface area of the droplets and therefore in an increased cloud albedo. Secondly, the absorption effect by black carbon (BC) often will be increased and thus lower the albedo of clouds [*Grassl*, 1975] and reduce the albedo increase of optically thin clouds that are more strongly influenced by the radius effect.

2. Evaluation of Satellite Measurements

[5] Our analysis of NOAA AVHRR data, i.e., the Pathfinder data set [*James and Kalluri*, 1994], from the late 1980s (4 years average) to the late 1990s (again 4 years average) over China shows an amazing result: The LPA increases only during summer southward of 30°N (Figure 1a). Northward of 30°N even a decrease becomes visible. During winter (Figure 1b) the LPA is decreased in nearly all regions. The highest decrease of LPA in winter from the late 1980s to the late 1990s occurred over polluted regions. This pronounced change with maxima higher than 5% is unique if compared to North America and Europe. The heterogeneity of the change in China, i.e., higher values of change in densely populated and industrialized areas, suggests that changing air pollution is the main cause.

[6] Since air pollution in China generally was much more pronounced during the late 1990s than during the late 1980s [*Xu*, 2001] the negative LPA change cannot be explained by a strong decrease of sulphur dioxide (SO_2) emissions, as took place enforced by Clean Air Acts in North America over recent decades and in Europe since the early 1990s. In Europe, for example, during this time an extreme emission reduction by about 23 Tg y^{-1} sulphur, which is not seen at all in China, was the reason for a lowering of low and medium level cloud albedo of about 2–3% [*Krüger and Graßl*, 2002]. Two key questions arise from this conspicuous regional climate change:

- Has cloud cover changed as a consequence of increased air pollution?

- Is brown haze responsible for the reduction of the local planetary albedo?

[7] First hints regarding the influence of indirect aerosol effects on LPA change can be derived by separating the total LPA change into the contribution by low and medium level clouds on one hand and the residual change of all other atmospheres on the other. The residual LPA change therefore contains cloudless atmospheres (including haze), partially cloud covered pixels and high level clouds. We expected, in case the aerosol is absorbing, that the absorption effect becomes visible for the often optically thick low and medium level clouds while the radius effect is dominant for the much lower mean optical thickness of the partly cloudy atmospheres. In case of a strong increase of absorbing aerosol concentration, which might be due to so-called brown haze or dust or both in a mixture, for clear or partially cloud covered pixels a decrease of LPA must become also visible for the residual atmospheres.

[8] The residual LPA changes in the Gobi desert and around Liuzhu north-west of Hong Kong confirm that aerosol effects have these pronounced influences on residual LPA. In the Gobi desert the LPA of low and medium level clouds increases by more than 3% which indicates an effect of decreasing cloud droplet radius (Figures 1c and 1d). However, these changes can not be explained alone by enhanced emissions of mineral dust through sand storms. The seasonal dependency supports that particles of anthropogenic origin may have also a strong influence. The radius

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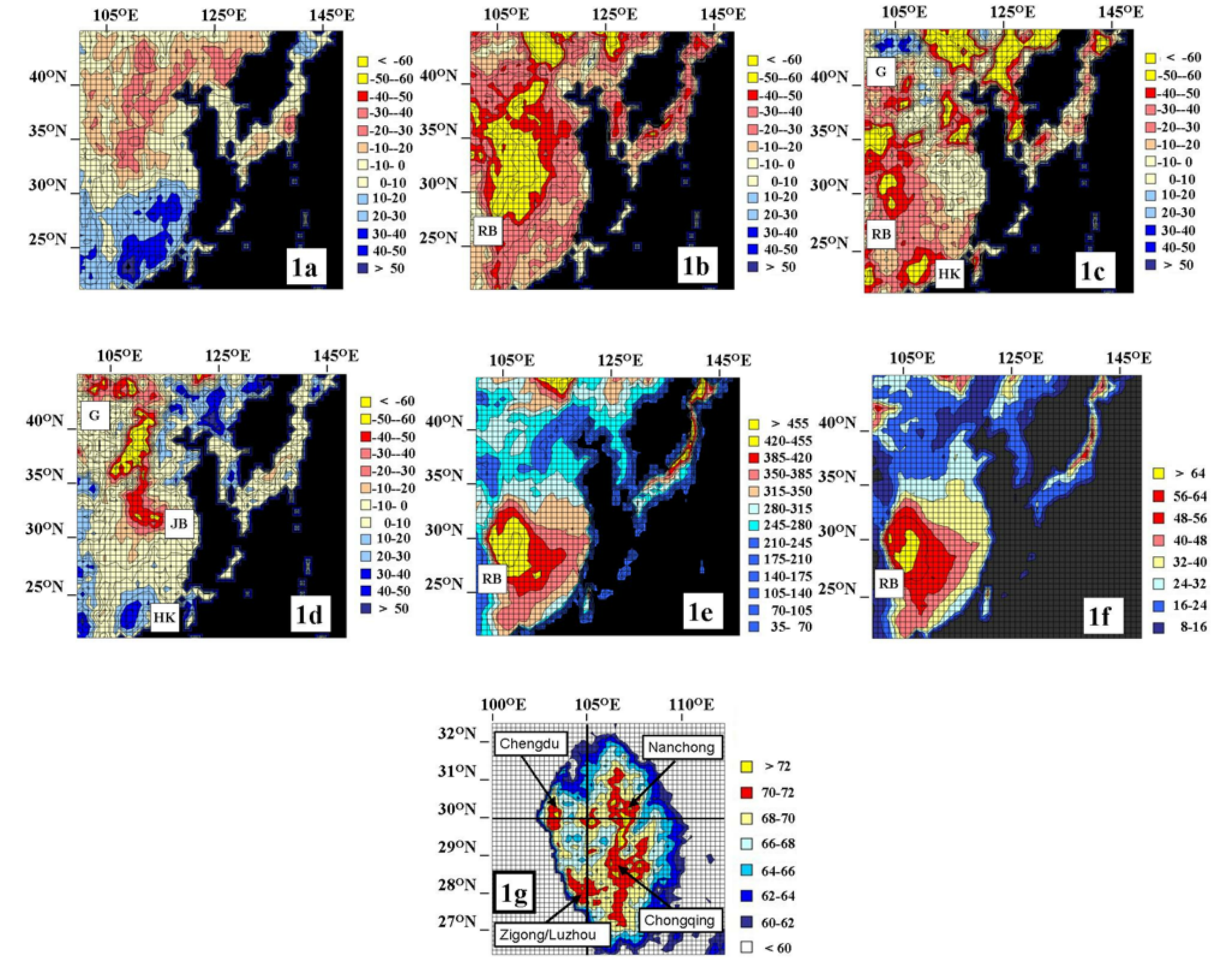

Figure 1. Changes of the local planetary albedo (LPA) in thousandth at ~0.8 μm wavelength (AVHRR, channel 2) from the late 1980s (1985, 1986, 1988, 1989) to the late 1990s (1996, 1997, 1998, 1999) over south-eastern Asia for summer, MJJA (a) and winter, JFND (b). The grid size is 1° longitude and 0.5° latitude. The area covers China, Mongolia, North Korea, South Korea, Japan and parts of the Pacific (in black). The Red Basin (RB), the Gobi desert (G), Hong Kong (HK) and the Jangtze Basin (JB) are indicated. The total mean LPA change is subdivided into the contributions of low and medium level clouds for winter (c) as well as into the residual change for cloudless atmospheres (including haze), plus partially cloud covered pixels and high level clouds (d). The maximum values of the mean local planetary albedo (e), in thousandth, and also of cover by low and medium level clouds (f, g), in percentage, occur in the Red Basin over densely populated regions (the winter for the late 1990s is shown).

effect is most pronounced during the summer monsoon when anthropogenic aerosols are advected to the north from emission areas in southern and eastern China. In addition the LPA decrease of the residual atmospheres for winter and summer in the Gobi desert indicates an increasing concentration of absorbing aerosols.

[9] During winter in southern China, where mean cloud optical thickness is much higher, and where major source regions of pollution exist, the strongest contribution of low and medium level clouds to the total decrease of LPA occurs. In Liuzhu north-west of Hong Kong for example the maximum decrease from the late 1980s to the late 1990s amounts to more than 5%. At the same time in the same area the LPA increased for the residual atmospheres (Figures 1c and 1d). This clearly confirms that indirect aerosol effects, i.e., the absorption effect for low and medium level clouds and the radius effect for residual atmospheres, change the LPA.

[10] In order to investigate the strong decrease of LPA in more detail we focused on southern China where present day world wide highest fine aerosol optical depth was detected [*Kaufman et al.*, 2002]. Here in the Red Basin an even larger LPA decrease occurs than in the region north of Hong Kong. The Red Basin at about 30°N latitude and 105°E longitude has a dimension of more than 300 × 300 km^2 and is surrounded by high mountains in nearly all directions reaching up to 7500 m height. The area is characterized by dense population and includes important industrial branches based on hard-coal, oil and natural gas. The combination of high emission source strength and topography favour the accumulation of pollutants in the lower troposphere. Over the Red Basin the strongest decrease

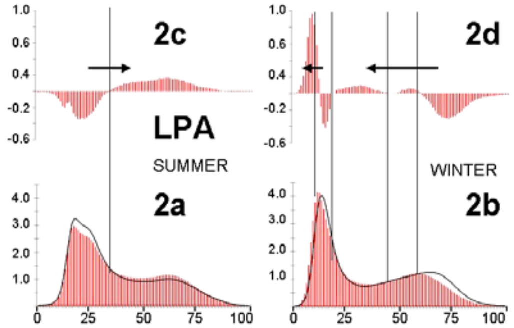

Figure 2. Frequency distribution of LPA (in percent per LPA interval of 1% width) south of 32.5° N over southern China (including the Red Basin and the lower Jangtze Basin) for summer (a) and winter (b) during the late 1980s (solid black line) and the late 1990s (red). In addition the differences between the late 1980s and the late 1990s are detailed in (c) and (d). During summer higher LPA is more frequent (see arrow indicating the shift). In winter there is a shift to lower LPA when the absorption effect in clouds and brown haze is dominating.

from the late 1980s to the late 1990s occurs for winter in areas of highest LPA (Figure 1e). The values decline with distance to the basin.

[11] The analysis of cloud cover by low and medium level clouds (Figures 1f and 1g) in this area shows: A maximum exists just over the Red Basin. As for LPA the values for cloud cover continuously decline over several hundred kilometres distance to the basin. The comparison of the late 1980s and the late 1990s for distinct LPA classes shows that there is only a rather small change of cloudiness in winter (Figure 3a). Therefore the strong LPA changes in winter can not be explained by a reduction of cloudiness.

[12] Generally also an influence of brown haze on LPA is possible. If the haze layers become more intense then the LPA changes of the residual atmospheres must show it. Indeed, northward of 30°N there is an increase of haze (Figure 1d). However, over the Red Basin where the strongest decrease of LPA takes place we see no indication for a strong increase of haze indicated by a lowering of LPA.

[13] Therefore we can answer the second question as follows: We detect an increase of brown haze in some regions, but brown haze has only a limited contribution on the total decrease of LPA during winter from the late 1980s to the late 1990s. The main decrease by brown haze occurs north of the Jangtze Basin.

[14] The main processes causing a change of LPA are indicated by the frequency distribution of LPA (Figures 2a and 2b). The change of the LPA frequency distribution for winter points to two major shifts: One for optically thick clouds at high LPA and one for the cloud-free part at the lower limit. At the latter the frequency distribution function shows a clear shift to low LPA. Since generally the LPA for the clear atmosphere tends to increase by pollution, a slight decrease can only be explained by dominance of the absorbing component, i.e., brown haze. South of 32.5°N this is mainly due to the emissions in the Jangtze Basin. However, the strongest change occurs for optically thick clouds that show LPA reduction. Again it becomes visible: Brown haze reduces the LPA in China, but haze in cloudless areas alone can not explain the strong decrease of LPA as seen for example in the Red Basin. In contrast to the winter albedo reduction LPA is clearly increased in summer south of 32.5°N. This might be due to an increasing radius effect because major changes are detected for the residual atmospheres.

3. Discussion and Conclusions

[15] Since we identified changing cloud optical properties as the major reason for the downward trend of LPA in southern China the characteristics of these changes are discussed now in more detail. For that a subdivision of the area south of 32.5° into areas of different mean LPA around the Red Basin (Figure 1e) is useful. Two major characteristics arise from the subdivision: Firstly, the LPA of medium and low level clouds for winter shows a much stronger decrease with total LPA (equivalent with distance to the Red Basin) than during summer (Figure 3a). This is due to the much lower mean cloud optical thickness, as seen from mean LPA for low and medium level clouds, in the areas north-east of the Red Basin. Secondly, the winter cloud cover from the late 1980s to the late 1990s for all areas is nearly identical (Figure 3a). Therefore no major climate change for clouds is seen which could explain the changing LPA. Since a much higher reduction of LPA (Figure 3b) occurs in areas of higher cloud amount and

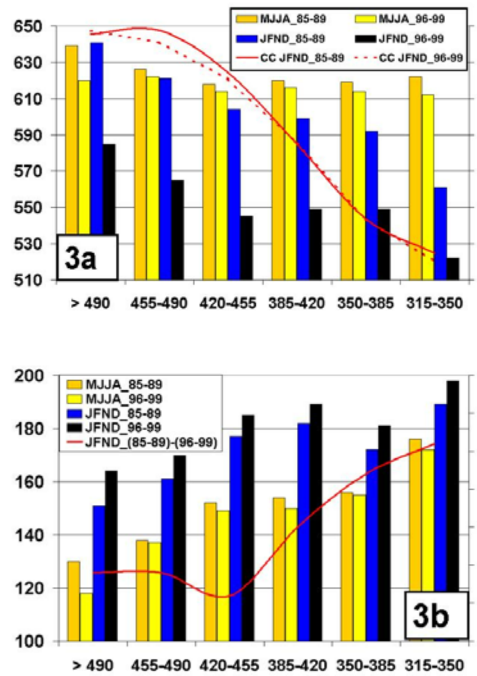

Figure 3. (a) LPA of low and medium level clouds (left axis, coloured columns) and cloud cover for winter (right axis, red lines) over southern China south of 32.5° N in thousandth as a function of mean reflectance in and around the Red Basin (late 1990s, Figure 1e). (b) Standard deviation (left axis, coloured columns) and LPA change of low and medium level clouds (right axis, solid red line) in thousandth (same areas as in (a)).

higher optical thickness, with maximum values just over the densely populated regions of the Red Basin (Figure 1g), the LPA changes are due the absorption effect. The analysis of temperature trends in China [*Yu et al.*, 2001] supports our conclusion that there must be enormously high concentrations of absorbing aerosols during winter. The maximum LPA decrease (Figures 3a and 3b) in the northern part of the Red Basin can be explained by a high degree of pollution around Chengdu and Nanchong and an advection of pollution from the Xian region.

[16] We get further evidence for this interpretation by the behaviour of the standard deviation which confirm an anthropogenic influence on cloud LPA (Figure 3b). In all areas in and around the Red Basin the variability is clearly higher in winter than in summer. This is due to the strong influence of black carbon which, if integrated into the cloud, reduces LPA so strongly that we can see a high difference between the cases of highly polluted and less polluted clouds. Therefore the high variability is an indication of the absorption effect as well. The same variance characteristics have been derived for Europe [*Krüger and Graßl*, 2002]. The increase of variability for all regions in winter shows evidence for increasing black carbon concentrations.

[17] In summer the absorption effect is much weaker, as in Europe, because of higher sulphate formation rates and higher boundary layers. Only in the source regions of pollution around densely populated regions in the Red Basin (Figure 3a and 1g) there is still a dominating influence of black carbon on summertime cloud LPA.

[18] Evidence for the radius effect is seen by the continuous decrease of standard deviation from remote regions to the source regions of pollution in the Red Basin. This is due for both summer and winter. It can be explained by the radius effect because it increases the LPA for optically thin clouds and therefore reduces the width of the frequency distribution for LPA of low and medium level clouds. The decrease of the standard deviation from the late 1980s to the late 1990s in summer also indicates an increase of pollution. The maximum change occurs in the Red Basin.

[19] We conclude that the increased cloud cover over the Red Basin is an indication for an additional indirect aerosol effect, the so-called lifetime effect. As a consequence of the radius effect it describes an increase in cloud lifetime and thus in cloud cover. Over the Red Basin continuously high aerosol number concentrations can lead to a nearly permanent radius effect with a considerably decreased effective radius of cloud droplets. Under those conditions coalescence is largely suppressed. Consequently the lifetime of clouds grows. Our study shows that mainly inside the Red Basin cloud cover is clearly higher in the regions around Chengdu, Nanchong, Chonquing and Zigong/Luzhu. These densely populated cities are strong sources of air pollution. The cloud lifetime effect over the Red Basin corresponds well to the precipitation decrease there in mid-summer during the last decades [*Xu*, 2001; *Rosenfeld*, 2000].

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