

## Can aerosols spin down the water cycle in a warmer and moister world?

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[1] Surface observations show puzzling evidence of reduced solar warming and concurrent increasing temperature during the last four decades. Based on climate simulations with the general circulation model of the Max Planck Institute in Hamburg we suggest that the interactions of greenhouse gas forcing plus direct, semi-direct and indirect aerosol effects on clouds explain this paradox. We argue that reductions in surface solar radiation due to clouds and aerosols are only partly offset by enhanced down-welling longwave radiation from the warmer and moister atmosphere. We conclude that the radiative imbalance at the surface leads to weaker latent and sensible heat fluxes and hence to reductions in evaporation and precipitation despite global warming. **INDEX TERMS:** 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 1655 Global Change: Water cycles (1836); 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; 3359 Meteorology and Atmospheric Dynamics: Radiative processes. **Citation:** Liepert, B. G., J. Feichter, U. Lohmann, and E. Roeckner (2004), Can aerosols spin down the water cycle in a warmer and moister world?, *Geophys. Res. Lett.*, 31, L06207, doi:10.1029/2003GL019060.

### 1. Introduction

[2] Temperature increased by 0.09K per decade between 1951 and 1989 over land [*Intergovernmental Panel on Climate Change 2001 (IPCC)*, 2001] and broadband global solar radiation declined by 7 W/m<sup>2</sup> on average between 1961 and 1990 at land sites in many regions of the world [Liepert, 2002; Stanhill and Cohen, 2001; Gilgen et al., 1998]. For example, strong reductions in global solar radiation occurred in the United States with 18 W/m<sup>2</sup> in thirty years, which was explained by increasing concentrations of anthropogenic aerosol particles and cloud changes [Liepert, 2002]. Anthropogenic aerosols are mainly comprised of sulphates, nitrates and organic and black carbon (soot). Aerosol particles scatter and in case of carbonaceous substances absorb sunlight a process which is called the direct effect. Heating of the aerosol layer due to absorption can cause dissolving of clouds (semi-direct effect). Anthropogenic aerosol particles additionally act as cloud condensation nuclei and increase cloud albedo (first

indirect effect) and cloud lifetime by suppressing drizzle primarily over the oceans (second indirect effect). Hence changes in aerosols and clouds affect the surface energy budget quite effectively besides global warming. Observations show that evaporation from pans declined steadily over the past 50 years in the Northern Hemisphere. Roderick and Farquhar [2002] argued that declining global solar radiation causes the decline in pan evaporation and concluded that the water cycle “dampens”. However, note that pan evaporation is “potential” and not “actual” evaporation. Observations of soil moisture show increasing tendencies of more than 1 cm per decade in large regions of Eurasia [Robock et al., 2000]. Concurrent significant decreases of global solar radiation at 60% of all sites in the former Soviet Union were reported [Abakumova et al., 1996] while during the same period precipitation rates did not change significantly in the former Soviet Union [Easterling et al., 2000]. We suspect that these observed changes in the water cycle are closely linked to changes in surface energy budget. Thus the main question posed in this study is: How do greenhouse gases and aerosol concentrations modify the climate such that the global water cycle can spin down during temperature increase and solar radiation decrease?

[3] Climate simulations suggest that greenhouse gas forcing intensifies the hydrological cycle with increasing global evaporation and precipitation rates by about 2.3 to 3.4% per Kelvin temperature increase [Douville et al., 2002; Wetherald and Manabe, 2002; Rind et al., 1992]. Conversely, if aerosol forcing is prescribed, a colder climate and a weaker hydrological cycle are simulated [Ramanathan et al., 2001]. In addition to the sign of the response, a major difference between greenhouse gas and aerosol forcing experiments is the hydrological sensitivity, which is defined as the ratio of global mean changes in precipitation rates and surface temperature. The hydrological sensitivity is larger in aerosol experiments alone because the forcing primarily affects the surface radiation budget, whereas in greenhouse experiments alone a major part of the forcing is felt within the troposphere [Boer, 1993; Allen and Ingram, 2002]. As previously shown by Roeckner et al. [1999] a combination of greenhouse gas and sulphate aerosol effects is already enough to weaken the hydrological cycle if sulphate aerosol concentrations are coupled to the cloud albedo (first indirect effect).

### 2. Model Description

[4] Here, we discuss the underlying mechanisms behind observed reduced solar radiation and global warming with the analysis of new climate simulations that take into account the direct, semi-direct, first and second indirect

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effect of aerosols and greenhouse gas forcing. The aerosol physics is fully interactive such that it can respond to greenhouse gas forcing and changes in meteorology.

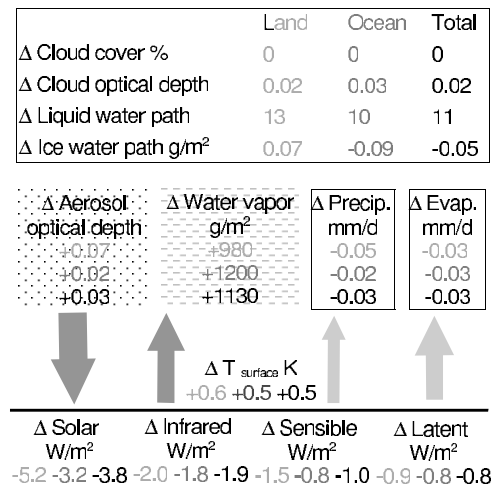
[5] The basic model is the ECHAM4 atmospheric general circulation model of the Max Planck Institute for Meteorology, which has been coupled to a mixed-layer ocean and a thermodynamic sea-ice model [Roeckner *et al.*, 1996]. ECHAM4 is a spectral atmospheric general circulation model applied here at T30 horizontal resolution with 19 vertical layers in a hybrid  $p$ - $\sigma$  coordinate system. The aerosol module includes a sulphur chemistry model that predicts aerosol mass distribution of sulphate, black carbon and organic carbon, sea salt, and mineral dust. Emission, transport, dry, wet deposition and chemical transformation are interactively calculated. A detailed description of the aerosol module is given by Feichter *et al.* [2004]. The aerosol number concentration at cloud base controls the formation of cloud droplets [Lohmann *et al.*, 1999]. Physical and optical aerosol properties are prescribed. This model is similar to the one reported by Roeckner *et al.* [1999]. New in the model is a parameterization of the cloud lifetime effect of aerosols, which modifies the precipitation formation efficiency for simulating the second indirect effect and absorbing carbonaceous aerosols for simulating the semi-direct effect [Lohmann *et al.*, 2000; Lohmann and Feichter, 2001].

[6] The first simulation was performed with pre-industrial aerosol and greenhouse gas conditions representative for pre-industrial mid-1880s. The second one was performed with present day greenhouse gas and aerosol concentrations representative for present day mid-1980s conditions. Each simulation was run for 75 years in an equilibrium mode. The statistics are taken from the last 50 years of each experiment. The total anthropogenic aerosol burden is 2 Tg of sulfur and carbon or 23% of the pre-industrial burden and 11% of the total anthropogenic burden is black carbon. The assumption is that the difference between present day scenario and pre-industrial scenario represents the effects of coupled anthropogenic greenhouse gases and aerosol forcings. Hence the underlying physics of these disturbances and its consequences can be studied but the temporal evolution of the real world cannot be captured.

### 3. Results

[7] Figure 1 summarises the resulting changes in surface fluxes and atmospheric parameters as averages over land, ocean and the globe (total). Over land the surface temperature increase is 0.6 K, which is close to the observed 0.65 K in the last century [IPCC, 2001]. While total cloud cover does not change the cloud liquid-water path and consequently cloud optical depth increases. Aerosol optical depth increases due to the direct anthropogenic aerosol effect. Associated with the increase in cloud and aerosol optical depth (and to a lesser extent increase in water vapor) is the reduction in net surface solar radiation of 5.2 W/m<sup>2</sup> over land and 3.8 W/m<sup>2</sup> globally. This is balanced by mean reductions in net infrared radiation of 1.9 W/m<sup>2</sup>, and reductions in sensible and latent heat fluxes of 1 and 0.8 W/m<sup>2</sup>, respectively.

[8] The simulated reduction in net solar radiation is slightly less than the observed 7 W/m<sup>2</sup> during the thirty-

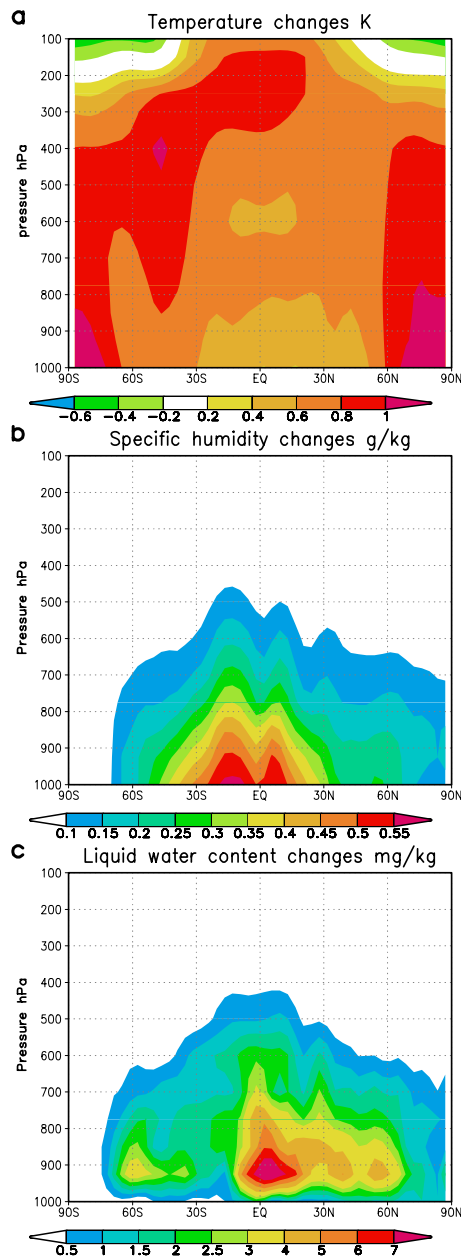


**Figure 1.** Simulated changes in atmospheric variables and surface energy and water fluxes. Changes are calculated as differences for a present day minus pre-industrial climate equilibrium experiments with a general circulation model where anthropogenic aerosol and greenhouse gas concentrations are modified. The arrows indicate direction and relative strengths of the energy fluxes.

year interval [Liepert, 2002]. Over North America, for example, the simulated reduction in surface solar radiation reaches a maximum of only 10 W/m<sup>2</sup> compared to the observed average of 18 W/m<sup>2</sup> in thirty years given by Liepert and Tegen [2002]. This underestimation of the decline in solar radiation might explain some of the differences between simulated and observed pattern of temperature change over the United States (see auxiliary material<sup>1</sup>). While the pronounced warming over the western part is well captured, the model simulates a slight warming over the Southeastern U.S. Observations indicate a cooling trend in the Southeast possibly due to increases in cloud and aerosol optical depth [Hansen *et al.*, 2001; Robinson *et al.*, 2002]. On the other hand, changes in total cloud cover are negligibly small in both observations and simulations. Also in good agreement with observations [Robock, 2000] are increases in soil moisture in Eurasia by up to 5%.

[9] The global reduction in net surface solar radiation in the model is balanced by reductions in net infrared radiation, sensible and latent heat fluxes (Figure 1). Thus these climate simulations reproduce the observed paradox of global warming and solar radiation reduction when greenhouse gas forcing, direct, semi-direct and indirect effects of major aerosols are included. As a consequence of the reduced latent heat flux, the global water cycle spins down. It is worth noting that changes in the overall intensity of the hydrological cycle are not only controlled by the availability of atmospheric moisture due to warming, but primarily by the availability of energy at the surface [Boer, 1993; Allen and Ingram, 2002]. Our findings contradict former findings (listed above) and the common assumption of an intensification of the hydrological cycle in a warmer climate with a moister troposphere. In our model simulations, aerosol

<sup>1</sup>Auxiliary material is available at <ftp://ftp.agu.org/apend/gl/2003GL019060>.



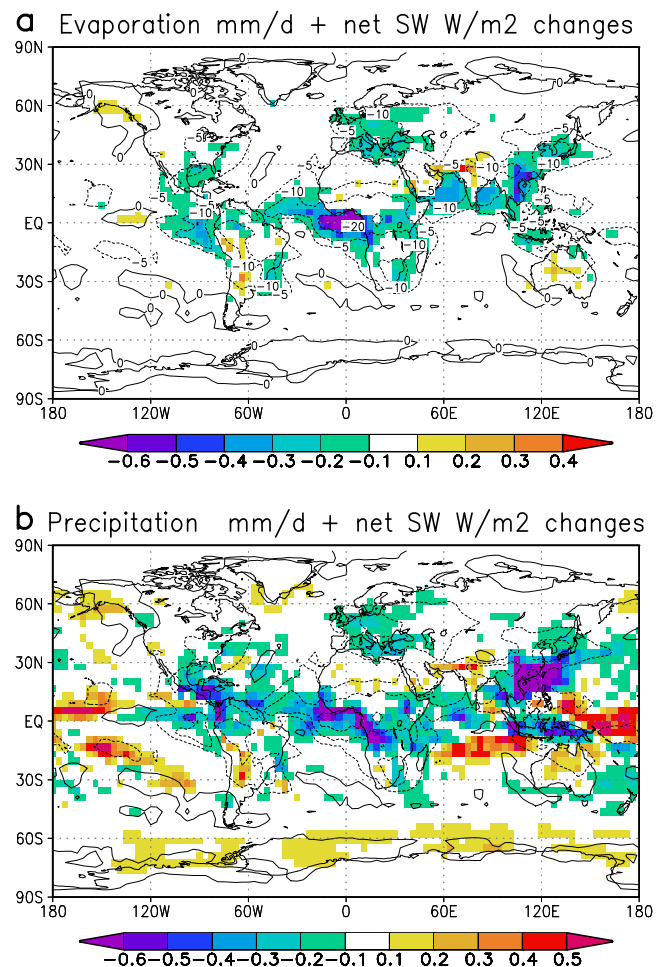
**Figure 2.** Simulated latitude – height changes of annual mean (a) temperature, (b) specific humidity and (c) liquid water content for present-day minus a pre-industrial climate simulations with modified anthropogenic aerosol and greenhouse gas concentrations.

effects are large enough to reduce the availability of total radiative energy at the surface despite global warming, so that the non-radiative fluxes decline and the global water cycle spins down.

[10] The strongest warming is found in the upper tropical troposphere, extending into the Southern Hemisphere, and also at high latitudes (Figure 2a). The specific humidity follows the general temperature increase as implied by the Clausius-Clapeyron relationship (Figure 2b). Water vapor residence time (total water vapor content divided by precipitation rate) is a measure for the turnover time of the hydrological cycle. This time increases by half a day in our

experiment. This increase is in accordance with greenhouse gas only simulations of, for example, *Douville et al.* [2002]. Associated with the enhanced availability of atmospheric moisture is a significant increase in liquid water content of clouds and subsequent increase in cloud optical depth (Figure 2c). Cloud cover, which is a function of relative humidity in the model, shows a slight decrease at mid levels of the midlatitudes (not shown). The second indirect effect, which results in suppressed drizzle formation and, hence, longer cloud lifetime might at least partly be responsible for the slight increase in low level cloudiness. High level cloud coverage is also slightly increased. None of these changes are significant and the total cloud cover is unchanged.

[11] As shown in Figure 3a, the surface evaporates less in regions where solar radiation is reduced due to changes in cloud and aerosol optical depth. Whereas precipitation changes (Figure 3b) are more widespread as a result of changes in circulation, particularly over the tropical oceans. Rainfall increases over the southern Indian Ocean and the equatorial Pacific and decreases over the equatorial Atlantic Ocean. However, the simulated precipitation changes do not



**Figure 3.** Simulated changes in (a) evaporation (colors) and net surface solar radiation (contours) and (b) precipitation (colors) and net surface solar radiation (contours). Model results are differences of present-day minus pre-industrial climate simulations with modified anthropogenic aerosol and greenhouse gas concentrations.

match with available observational trends over land (Climate Research Unit Data set, see auxiliary material). Between 30°N and 30°S rainfall rates generally increased between 1910 and 1980 and declined in the two decades afterwards. In the mid latitudes between 30°N and 60°N rainfall anomalies declined during the first three decades of the century and increased afterwards.

[12] The following remarks are important. The simulated increase in liquid water path is significant in large areas of the globe, but the parameterization of the cloud lifetime effect might be exaggerated in this model version [Lohmann and Lesins, 2002]. On the other hand, the direct aerosol effect seems underestimated in most models including this one [Kinne *et al.*, 2003]. Furthermore, the results are obtained by instantaneous increases of greenhouse gases and aerosols from a pre-industrial to a present day scenario. Hence the temporal climate evolution cannot be captured which hampers interpretation of the results. For example, in the recent decade of the 1990s reductions of aerosol concentrations were observed in many industrialised countries. Land use change may also have contributed to changes in the hydrological cycle during the last century, which is also not included in the model.

[13] In conclusion, we were able to explain the observed global temperature increase, a moister troposphere and reduced surface solar radiation when greenhouse gas forcing and direct, semi-direct and indirect aerosol effects are combined in the model simulations. We conclude that the hydrological cycle spins down in such a scenario and the residence time of water vapor increases. Despite the uncertainties of climate model studies in general and equilibrium experiments in particular, the described results are evidence of the importance of aerosol-cloud interactions in climate. This study indicates that these interactions together with realistic increases in anthropogenic aerosols are able to modify the hydrological cycle through surface energy budget modifications and subsequent reduction in evaporation to the extent that it can spin down despite global warming.

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