critical assumption that the depletion to withdrawal ratio is globally constant at 15%. However, this ratio can be as large as 90% in dry regions[4]. Furthermore, we are not convinced that sufficient observations exist to ascertain that there are not 50 to 70 similarly depleted systems such as the High Plains aquifer and that our estimate is grossly out of bounds. Instead, we suggest that our estimate is higher than other available estimates[2,4,6,7] mainly because long-distance water diversion is not taken into account, irrigation demands are always assumed to be met, and global-scale input data, in particular precipitation, are highly uncertain.

Fourth, regarding Konikow's comments on the seepage from large reservoirs, in our approach[8] seepage losses are significant only in the initial stage of reservoir filling. Moreover, our result is based on the actual reservoir storage instead of its capacity.

In summary, Konikow's comment calls for more attention to finer details in modelling approaches. However, we have extensively validated our model[9,10] and consider our approach to be reliable. We suggest that until more comprehensive observations are collected globally, it is premature to question one estimate by citing another. ❐

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Yadu N. Pokhrel[1,2,3]*, Naota Hanasaki[4], Pat J.-F. Yeh[1], Tomohito J. Yamada[2], Shinjiro Kanae[5] and Taikan Oki[1]

[1]Institute of Industrial Science, The University of Tokyo, 153-8505 Tokyo, Japan, [2]Faculty of Engineering, Hokkaido University, 060-8628 Sapporo, Japan, [3]Department of Earth and Planetary Sciences, Rutgers University, Piscataway, New Jersey 08854, USA, [4]National Institute for Environmental Studies, 305-8506 Tsukuba, Japan, [5]Department of Mechanical and Environmental Informatics, Tokyo Institute of Technology, 152-8552 Tokyo, Japan.
*e-mail: pokhrel@rainbow.iis.u-tokyo.ac.jp

Water vapour affects both rain and aerosol optical depth

To the Editor — In a nice statistical analysis of Tropical Rainfall Measuring Mission (TRMM) and Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data, Koren *et al.*[1] show that higher rain rates are associated with higher aerosol abundances over a range of conditions and regions. They assert that this relationship is indicative of aerosol-induced cloud invigoration and rain intensification. As Koren *et al.* point out, correlation does not imply causality, and their analysis can only support, rather than prove, their hypothesis. As the concentration of aerosols and cloud condensation nuclei cannot be measured from space, especially in cloudy situations, Koren *et al.* use clear-sky aerosol optical depth (AOD) as a proxy for aerosol abundance. Here, we argue that water vapour influences both precipitation, which depends on the availability of water, and aerosol optical depth, through aerosol humidification[2]. We suggest that aerosol humidification could account for the relationship between aerosols and rain rate proposed by Koren *et al.*

We performed the same analysis as Koren *et al.* to examine the relationship between rain rate and aerosol optical depth, but using one year of daily data from a global climate model simulation in which indirect effects of aerosol on clouds and precipitation were turned off[3]. Like Koren *et al.*, we exclude grid boxes with no precipitation, and define

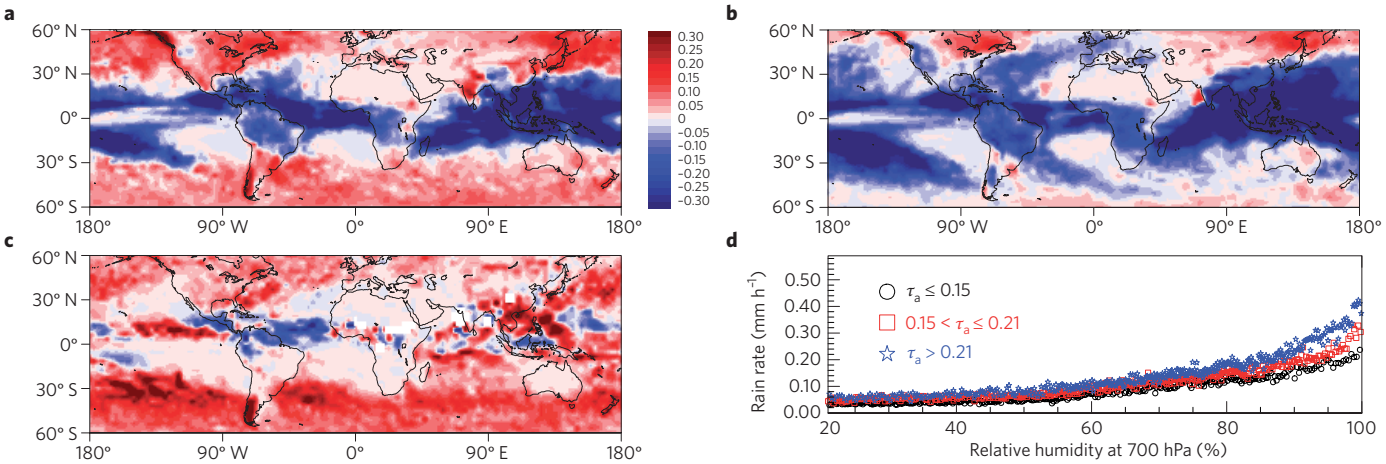

Figure 1 | Differences in rain rate (mm h^{-1}) between the polluted and clean conditions. **a**, Map using the AOD and meteorological data from the climate model. The colour scale relates to **a**–**c**. **b**, Map using the dry AOD and meteorological data from the climate model. **c**, Map using the ECMWF 48–72 hour forecast AOD and meteorological data for June, July and August 2003. **d**, Histogram of the rain rate as a function of the relative humidity at 700 hPa for the three AOD terciles using the ECMWF global AOD and meteorological forecast data. Each data point is an average over 500 model grid boxes.

the clean and polluted cases as corresponding to the first and third terciles of the AOD (discarding values larger than 0.3). Given the model resolution, our analysis only picks up large-scale variations in water vapour and excludes any small-scale impact of clouds on AOD, which Koren *et al.* have also tried to minimize. Like Koren *et al.*, we observe greater rain rates in polluted versus clean conditions over most of the mid-latitudes, but in the absence of any influence of aerosols on clouds (Fig. 1a). In sharp contrast to Koren *et al.*, we observe lower rain rates in polluted versus clean conditions in tropical convective regions.

Repeating the analysis using the modelled dry AOD (Fig. 1b) — that is, in the absence of aerosol humidification — demonstrates the large impact that aerosol humidification has on the relationship between rain rate and AOD. In most regions, rain rates are lower in polluted compared with clean conditions. This negative relationship between rain rates and AOD, which is the opposite to that documented by Koren *et al.*, is most likely due to the scavenging of aerosols by rain.

The discrepancy between model and satellite data in the tropics (in the presence of aerosol humidification) needs further investigation; it could be due to modelling or sampling issues in regions where convective rainfall is high. Aerosol-induced invigoration of clouds and/or intensification of rain — which is not included in the model — could also play a role.

Substitution of the global climate model data for aerosol and meteorological forecast data from the European Centre for Medium-Range Weather Forecasts (ECMWF)[4] — which also excludes aerosol indirect effects — gives similar results (Fig. 1c). That is, rain rates are greater in polluted conditions, despite the absence of aerosol–cloud interactions in the model, except in the tropics where the relationship is reversed. Slicing the ECMWF data into bins of equal relative humidity at a given pressure level does not remove the effect (Fig. 1d).

We conclude that aerosol humidification has a large impact on the relationship between AOD and rain rate presented by Koren *et al.*, and that discriminating the data into classes of pressure vertical velocity and/or relative humidity[5] does not eliminate these meteorological effects. We would also like to suggest that an apparently ubiquitous relationship between rain rate and AOD may have different reasons (such as aerosol humidification, wet scavenging and perhaps invigoration) in different regions. ❐

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Olivier Boucher[1]* and Johannes Quaas[2]
[1]Laboratoire de Météorologie Dynamique, IPSL/CNRS, UPMC, 4 place Jussieu, 75252 Paris Cedex 05, France, [2]Institute for Meteorology, Universität Leipzig, Stephanstrasse 3, D-04103 Leipzig, Germany. *e-mail: olivier.boucher@lmd.jussieu.fr

Authors' reply — We thank Boucher and Quaas for their interest in our paper, but strongly disagree with their conclusions. In our analysis[1], aerosol optical depth was on average 2.5 times higher in polluted compared with clean conditions. Here, we use basic hygroscopic growth and radiative transfer calculations to argue that aerosol humidification cannot account for this difference.

To bound the aerosol humidification effect — and calculate the relative humidity differential required to explain a 2.5-fold difference in aerosol optical depth — we performed detailed radiative transfer calculations[2] for a range of coarse and fine aerosol size distributions and compositions, for a constant aerosol concentration. As hygroscopic growth is highly nonlinear with relative humidity, the difference in aerosol optical depth due to humidification depends on the relative humidity range selected. For a highly hygroscopic aerosol that readily takes up water, a 2.5-fold reduction in aerosol optical depth can be achieved if the average relative humidity is reduced; for example, from 95% to 77% or from 90% to 55%. For a less hygroscopic aerosol, the same reduction can be achieved by a relative humidity drop from 95% to 65%, or from 90% to 3%. Note that the relative humidity differential required to explain a 2.5-fold difference in aerosol optical depth grows as the background relative humidity declines.

We argue that such differences in relative humidity are not realistic for cloud fields that form in the same location and season, such as those examined in our study[1]. To validate our main statement here, we have analysed over 30 years of atmospheric sounding data in cloud fields, revealing an average relative humidity of around 76% for the maritime cloudy lower troposphere (±10%) and 62% (±15%) for the continental lower troposphere. The variance is further reduced if the data is limited to similar meteorological conditions, as we do in our study by sorting the data into similar updraft or relative humidity regimes[1,3]. Such relative humidity differences result in AOD differences on the order of 10%, as opposed to 250%, as observed in our study[1].

Furthermore, relative humidity declines exponentially with increasing distance from a cloud field[2]. As a result, the influence of aerosol humidification will be greatest within the first few tens of metres around each cloud. The MODIS algorithm filters out pixels within 1 km of detectable clouds, where the influence of hygroscopic growth would be maximal[4]. Furthermore, 25% of the brightest pixels are rejected within each 10 × 10 km aerosol retrieval box. Both of these measures would significantly reduce the effect of relative humidity on aerosol optical depth retrievals[5].

We argue that if, as suggested by Boucher and Quaas based on their model output, one could produce all or most of the trend shown in our paper — that is, an increase in aerosol optical depth of 250% — then it raises the fundamental question of how well a climate model is able to represent the overall effect of aerosol hygroscopic growth without resolving small-scale variations in relative humidity, clouds and aerosols. ❐

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Ilan Koren[1]*, Orit Altaratz[1], Lorraine A. Remer[2], Graham Feingold[3], J. Vanderlei Martins[2,4] and Reuven Heiblum[1]
[1]Department of Environmental Sciences Weizmann Institute, Rehovot 76100, Israel, [2]Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA, [3]NOAA Earth System Research Laboratory (ESRL), Chemical Sciences Division, Boulder, Colorado 80305, USA, [4]Department of Physics and Joint Center for Earth Systems Technology, University of Maryland, Baltimore 21250, USA. *e-mail: ilan.koren@weizmann.ac.il

Correction

In the version of the Correspondence 'Hydroelectric carbon sequestration' originally published (*Nature Geosci.* **5,** 838-840; 2012), the 'Light temperature' label in Fig. 1 should have read 'Low temperature'. This has been corrected in the HTML and PDF versions.