# Estimation of the indirect radiative effects of aerosols on climate using the HadGEM-UKCA aerosol–chemistry climate model

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## 1. Introduction

Atmospheric aerosols have a significant effect on the Earth's radiative balance both directly, by scattering and absorbing radiation, and indirectly, through their effects on cloud properties. A crucial link between aerosol and cloud is the ability of aerosols to act as cloud condensation nuclei (CCN) on which cloud droplets form, a process known as aerosol activation.

An increase in the number of CCN leads to a greater number of smaller cloud droplets (for a cloud of constant liquid water content) with two main consequences: First, the larger surface area of a greater number of smaller droplets increases the cloud albedo (Twomey, 1974); Second, these smaller droplets are less efficient at coalescing to form raindrops which may increase the cloud amount and lifetime (Albrecht, 1989).

Aerosol activation is critically dependent on the size and composition of aerosols as well as the local supersaturation of water vapour. This study seeks to explicitly represent all of these factors by coupling the two-moment-modal GLOMAP-mode aerosol scheme (Mann et al., 2010), to a physically-based aerosol activation parameterisation (Abdul-Razzak and Ghan, 2000) within the new UK Chemistry and Aerosol (UKCA) sub-model of the Hadley Centre Global Environmental Model (HadGEM).

This model provides the opportunity for a detailed quantification of the direct and indirect radiative effects of anthropogenic aerosol.

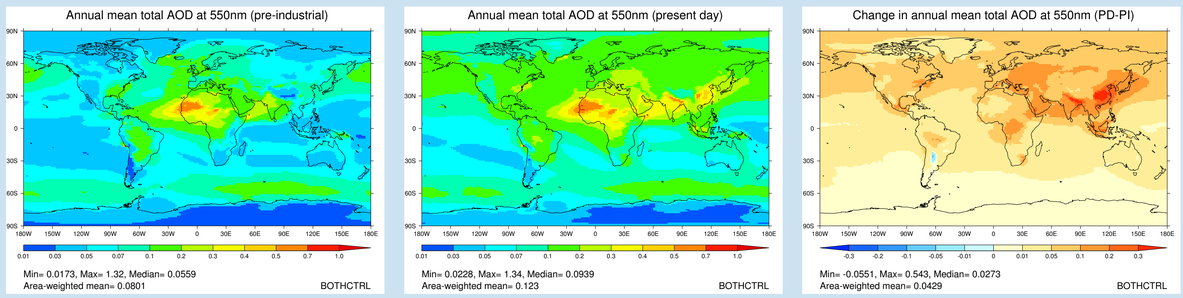
In the simulations shown, model meteorology is nudged to ECMWF re-analysis temperature and horizontal wind data for the year 2000. All figures show annual mean fields from a one-year simulation after a three-month spin-up period.

## 2. Aerosol modelling with GLOMAP-mode

GLOMAP-mode simulates a dynamically-evolving aerosol size distribution controlled by key microphysical processes (nucleation, coagulation, condensation and cloud processing) within a two-moment modal aerosol scheme transporting number and mass in each mode.

The configuration of GLOMAP-mode used here consists of an external mixture of five log-normal aerosol modes composed of internal mixtures of prognostic sea spray, anthropogenic black carbon, organic carbon and sulphate. Mineral dust is transported separately.

**Annual mean aerosol optical depth at 550 nm**

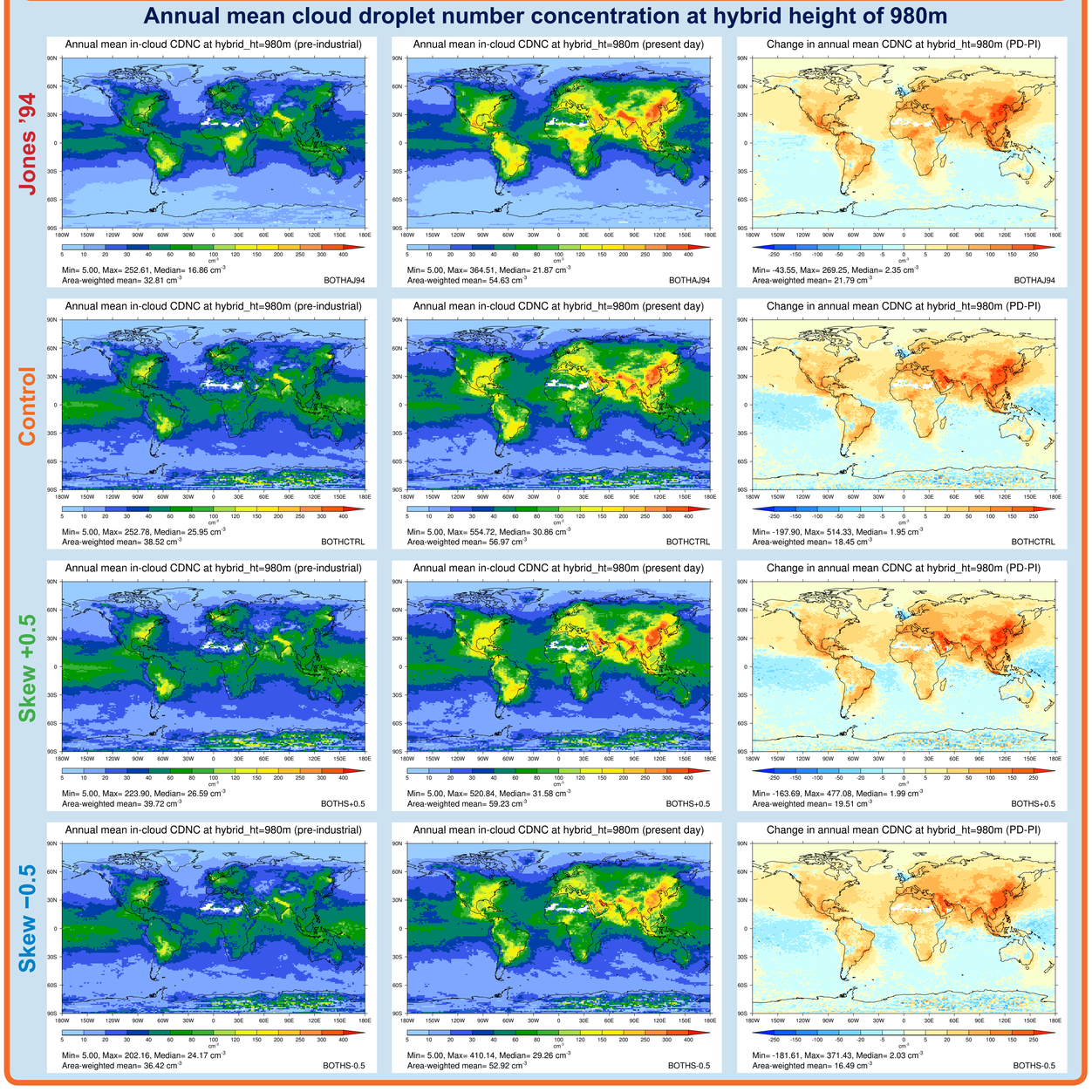



## 3. The effect of updraught velocity on cloud droplet formation

Variations in updraught velocity have a significant effect on the number of activated particles. In this study we have incorporated the sub-grid-scale variability of updraught with three different probability density functions (pdf) derived from the turbulent kinetic energy in the boundary layer. We use a Gaussian distribution of updraughts in the control experiment, and also show the effects of using skew-normal distributions with positive and negative skewness. We calculate the cloud droplet number concentration for each of 20 bins of updraught velocity and then calculate the expectation value when this function is weighted by the pdf. For comparison, we also show cloud droplet number concentration calculated by the empirical relationship of Jones et al. (1994).

| Reference | Experimental configuration of aerosol activation |
|---|---|
| Jones '94 | Cloud droplet number concentration calculated following Jones et al. (1994) |
| Control | Aerosol activation: Abdul-Razzak & Ghan (2000) with Gaussian pdf of updraught velocity; mean=large-scale updraught; $\sigma_w$=max(0.1 m/s, 0.7√(TKE)); 20 bins from 0 < w < 4$\sigma_w$ |
| Skew +0.5 | As control, but with skew-normal pdf of updraught velocity; skewness=+0.5 |
| Skew −0.5 | As control, but with skew-normal pdf of updraught velocity; skewness=−0.5 |
| Direct | Direct aerosol effects only; No aerosol activation; CDNC fixed at 100 cm$^{-3}$ over ocean and 300 cm$^{-3}$ over land. |

**Annual mean cloud droplet number concentration at hybrid height of 980m**

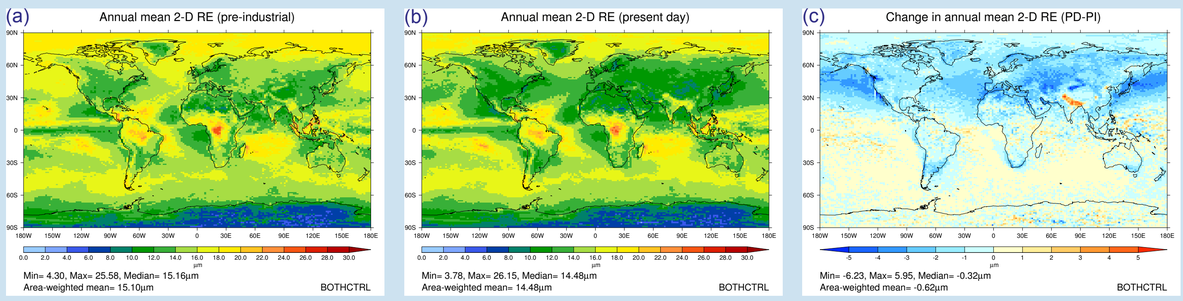



## 4. Modelling the indirect aerosol effects

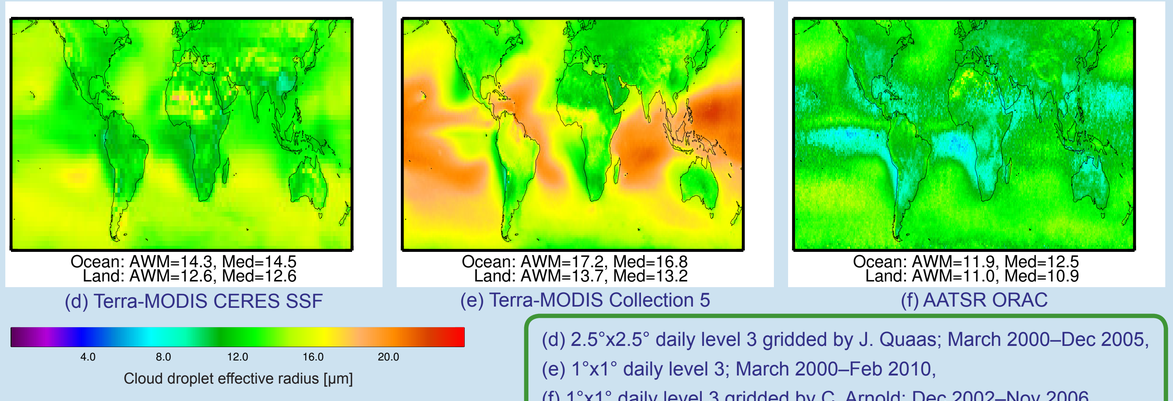
We approximate cloud droplet number concentration (CDNC) in warm clouds by the number of aerosols which activate at cloud base. To model the first indirect effect we calculate the cloud droplet effective radius ($r_e$) as a function of CDNC and cloud liquid water content following Martin et al. (1994). Figs (a)–(c) show a general decrease in $r_e$ due to increased aerosol. Present-day simulated $r_e$ (Fig. b) appear to compare well with satellite estimates (Figs d–h).

Secondary indirect effects are modelled by the dependence on CDNC of the rate of autoconversion of cloud water to rain water based on the method of Tripoli and Cotton (1980). Figs (i)–(k) show increases in liquid water path in regions of increased aerosol optical depth.

**Annual mean cloud droplet effective radius at cloud top**

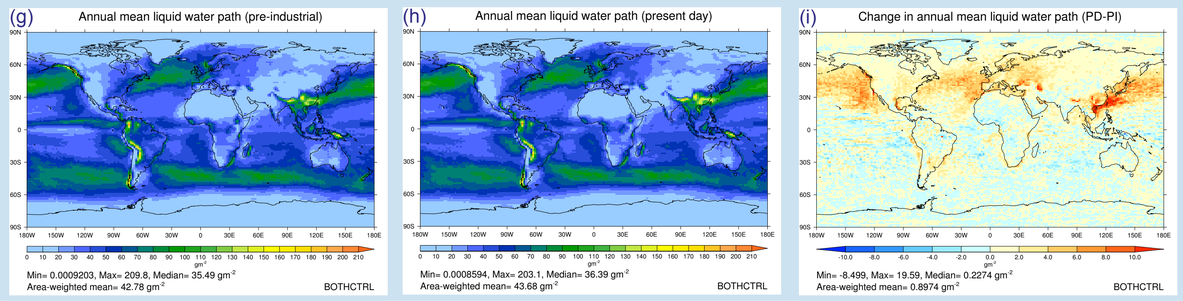



**Satellite-retrieved liquid cloud droplet effective radius**




(d) 2.5°x2.5° daily level 3 gridded by J. Quaas; March 2000–Dec 2005,
(e) 1°x1° daily level 3; March 2000–Feb 2010,
(f) 1°x1° daily level 3 gridded by C. Arnold; Dec 2002–Nov 2006,
Global ocean and land area-weighted means (AWM) and medians (Med) are provided below each map.

**Annual mean liquid water path**



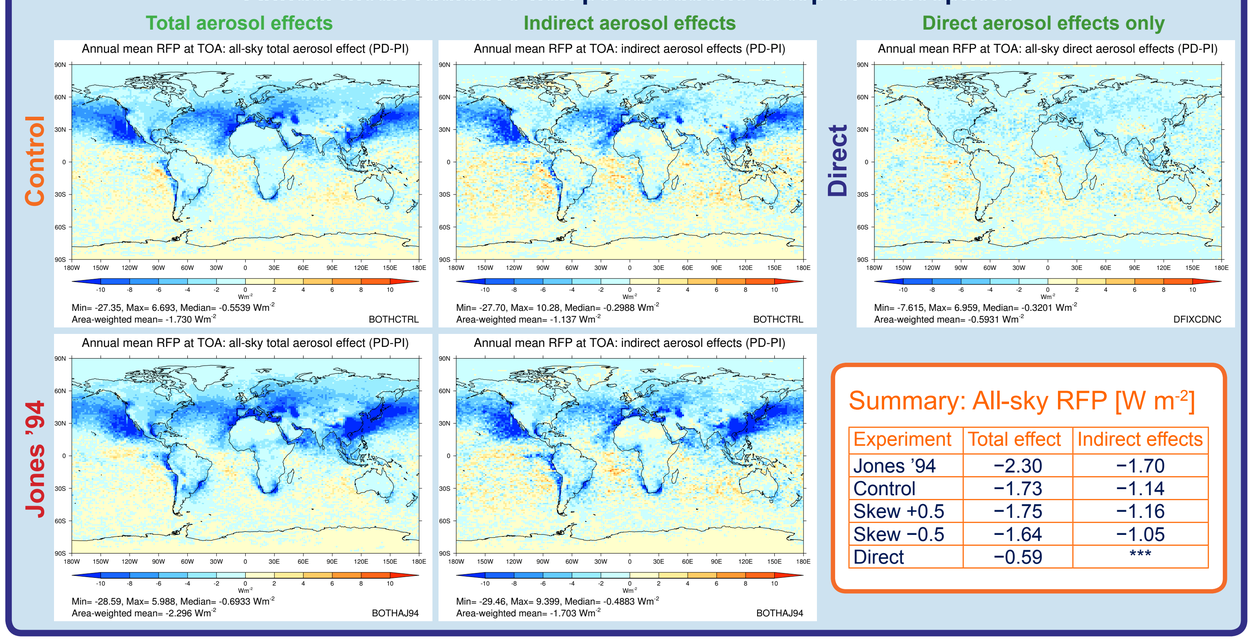

## 5. Radiative Flux Perturbations

For each experiment we estimate the radiative flux perturbation (RFP) due to the total anthropogenic aerosol effects derived from the difference in net radiation at the top of the atmosphere between one-year means of parallel present day and pre-industrial GCM simulations with fixed sea surface temperatures and sea-ice extent.

Since the Direct experiment only includes direct aerosol effects we may use this $RFP_{direct}$ to estimate the contribution to the total aerosol effects from the indirect effects in the other experiments by $RFP_{indirect} = RFP_{total} - RFP_{direct}$.

Results are summarised in the table below.

**Annual mean radiative flux perturbations at top-of-atmosphere**




**Summary: All-sky RFP [W m$^{-2}$]**

| Experiment | Total effect | Indirect effects |
|---|---|---|
| Jones '94 | −2.30 | −1.70 |
| Control | −1.73 | −1.14 |
| Skew +0.5 | −1.75 | −1.16 |
| Skew −0.5 | −1.64 | −1.05 |
| Direct | −0.59 | *** |

## 6. Conclusions

The use of an explicit aerosol activation scheme coupled to a microphysical aerosol model with dynamically-evolving size distributions and composition has allowed a more physically-based calculation of the cloud droplet number concentration than was previously possible.

The short simulations in this study give a preliminary estimate of the direct aerosol effect as −0.59 Wm$^{-2}$ and a total anthropogenic aerosol effect of −1.73 Wm$^{-2}$ from the control experiment.

Using a skewed distribution of updraught velocity alters the CDNC and hence RFP by up to 0.1 Wm$^{-2}$ but how this compares to other uncertainties inherent within the model remains to be seen.

Further work on the quantification of uncertainty in the indirect aerosol effects is definitely required.

## 7. References

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