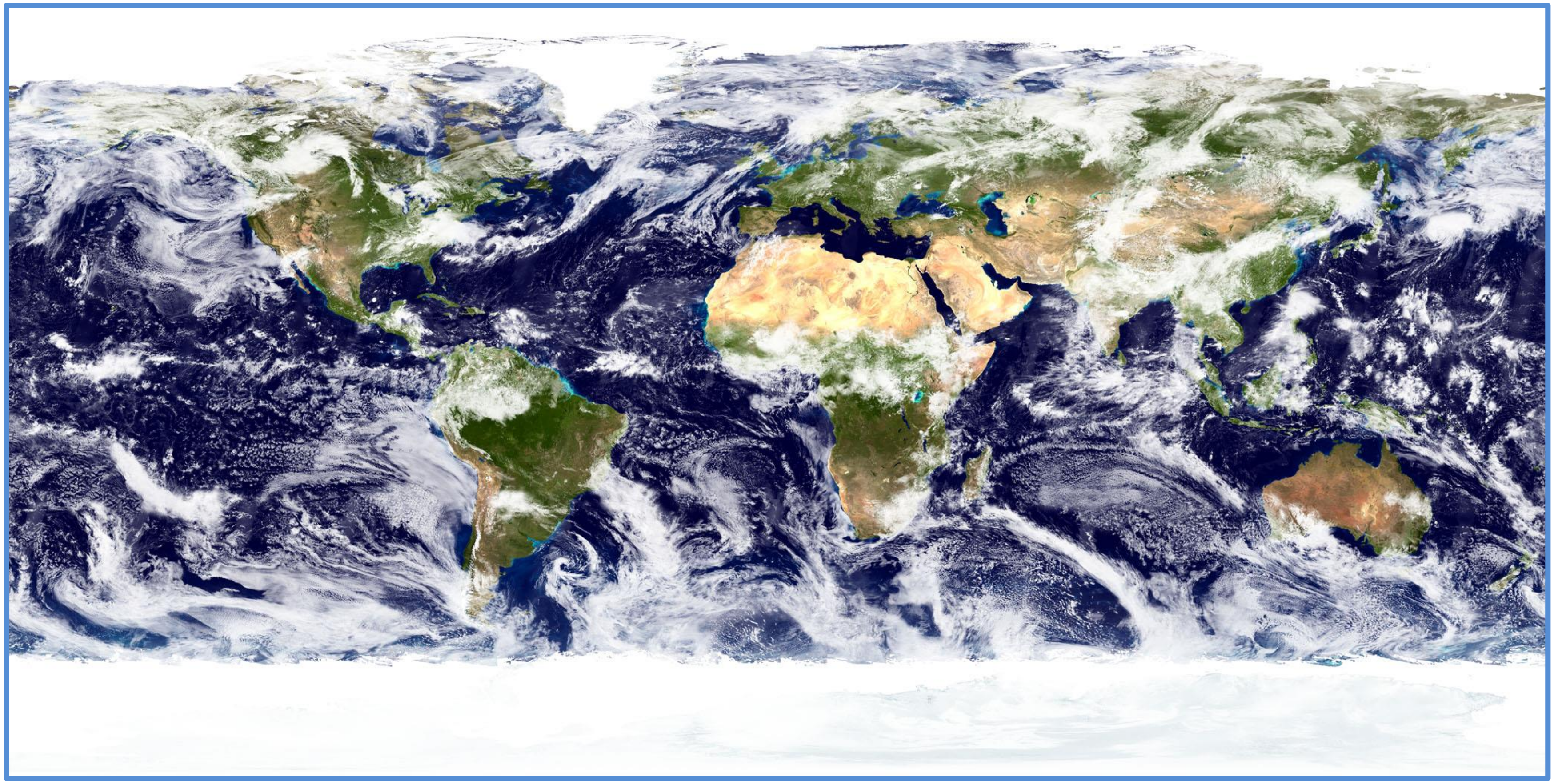
ACTIVATE – predicting cloud droplet number in the UKCA

Kirsty Pringle

CEMAC: Center of Excellence in Modelling of the Atmosphere and Climate

MODIS Visible Image

UNIVERSITY OF LEEDS



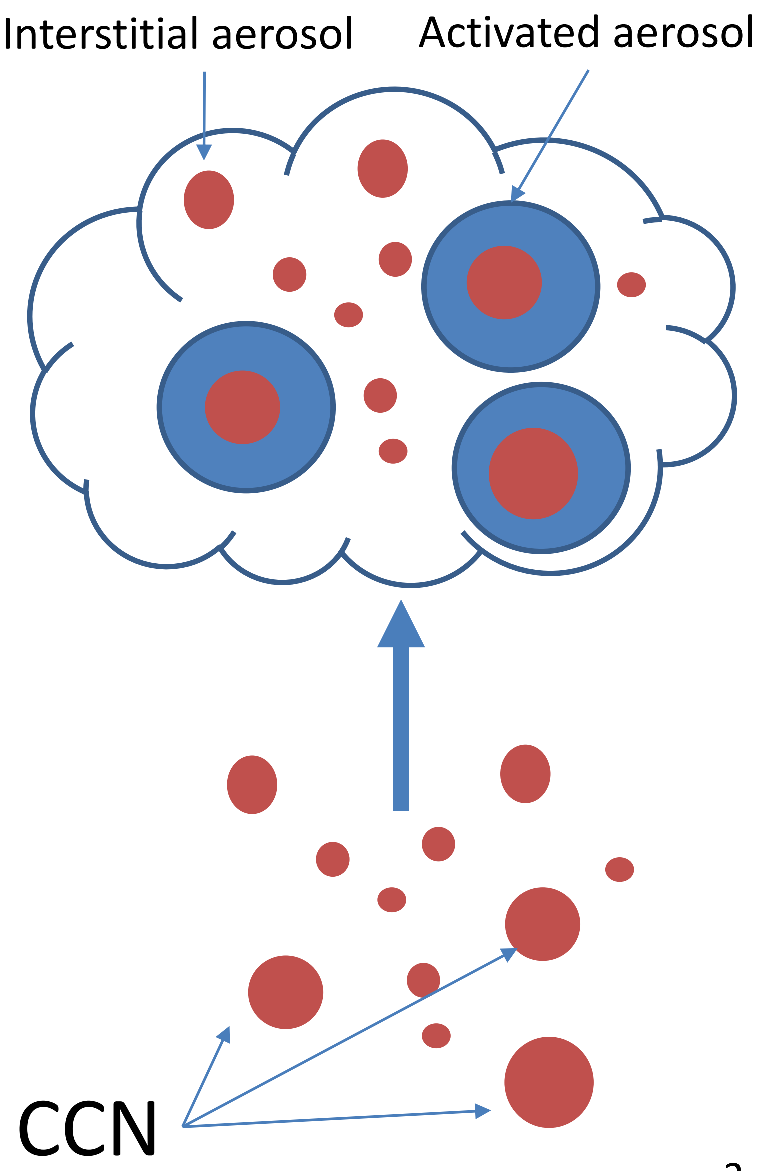
NASA Visible Earth: http://visibleearth.nasa.gov/view.php?id=57735

Composite image from the MODIS satellite.

What is cloud droplet number?

UNIVERSITY OF LEEDS

- Clouds form when rising air expands and cools.
- Clouds wouldn't form without aerosol particles (homogenious nucleation) – would need very high relative humidity.
- Instead cloud droplets form by condensation onto hygroscopic particles which act as **cloud condensation nuclei**.
- CCN = The subset of the aerosol population that "activates" to become cloud droplets, normally given relative to a reference superstautration (e.g. CCN0.2).
- The largest / most hydrophilic aerosol activate preferentially.



Aerosol / Cloud Interactions

UNIVERSITY OF LEEDS

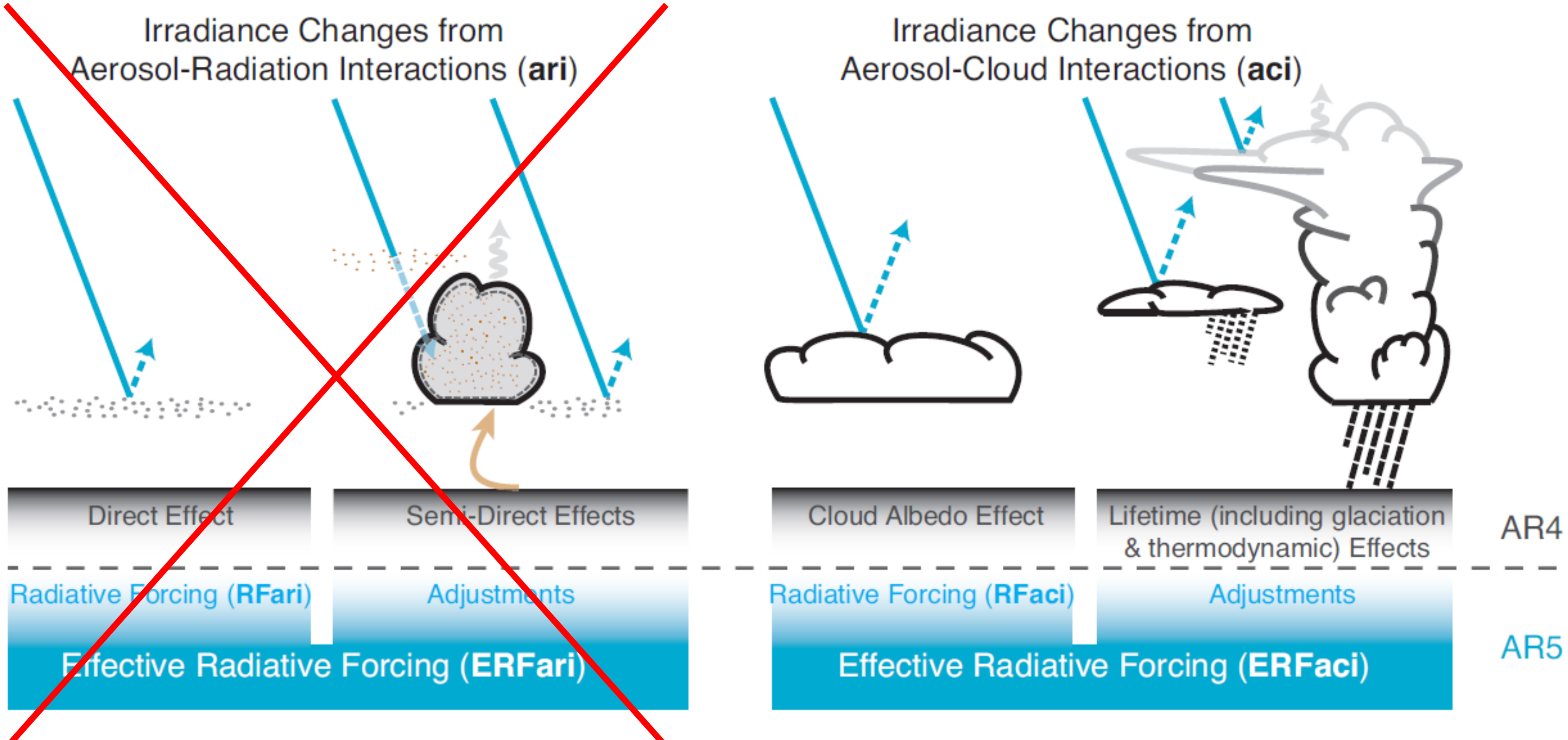


Figure 7.3 | Schematic of the new terminology used in this Assessment Report (AR5) for aerosol–radiation and aerosol–cloud interactions and how they relate to the terminology used in AR4. The blue arrows depict solar radiation, the grey arrows terrestrial radiation and the brown arrow symbolizes the importance of couplings between the surface and the cloud layer for rapid adjustments. See text for further details.

Do humans influence cloud properties?

UNIVERSITY OF LEEDS

Effect	AR4	AR5
More, smaller, droplets	Cloud albedo effect	Radiative forcing from aerosol cloud interaction. Rfaci
Cloud lifetime	Cloud lifetime effect	Adjustment

Aerosols can also affect clouds be changing the temperature profile of the atmosphere. (semi-direct effect).

Ship tracks – lines of bright cloud where ships have increased the local aerosol loading.
Images from NASA Earth Observatory.

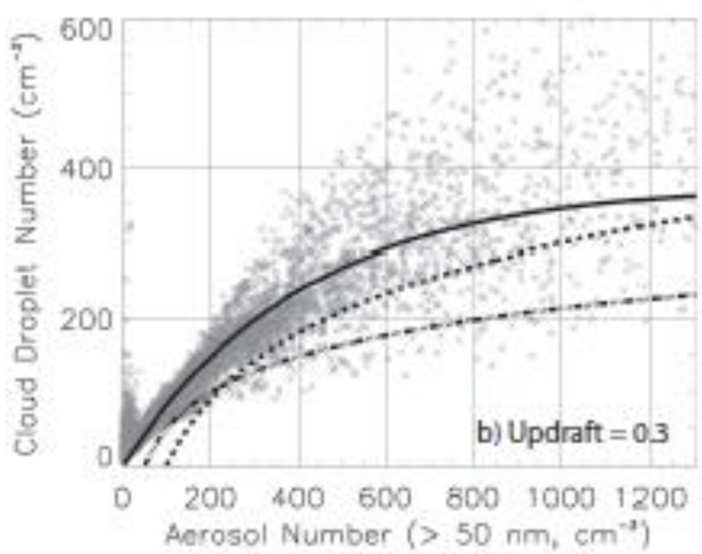
Predicting CDN in large-scale models

UNIVERSITY OF LEEDS

First estimates of cloud droplet number in global models took an **empirical** approach**.**

(empirical = based on observations rather than theory)

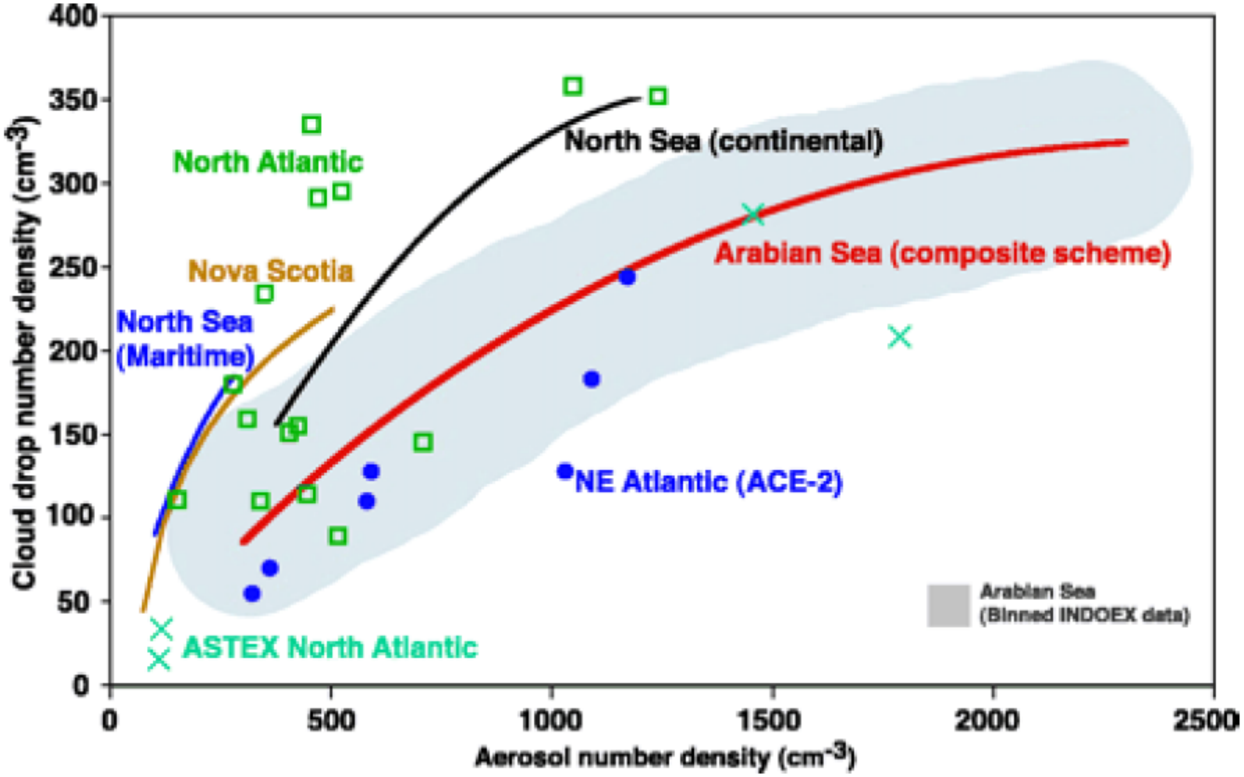
- Linked concentration of (i) aerosol number or (ii) mass to the CDNC.
- Simple, fast and easy to implement.
- Assumes a single, globally uniform relationship between aerosol and CDN.



Observations (solid line) show that CDN increases with increasing aerosol number.

Empirical Approaches

UNIVERSITY OF LEEDS



Summary of the relationship between aerosol number and observed CDN in different regions.

Ramanathan et al. (2001, Science)

In the atmosphere, the number of cloud droplets formed depends on the **size** and **chemical composition** of the **aerosol**. And also the meteorological conditions, temperature, pressure and importantly the **updraft velocity** (more on this later).

Microphysical approaches – an alternative to empirical treatment

"Köhler theory describes the process in which water vapour condenses and forms liquid cloud drops, and is based on equilibrium thermodynamics. It combines the Kelvin effect, which describes the change in saturation vapour pressure due to a curved surface, and Raoult's Law, which relates the saturation vapour pressure to the solute."

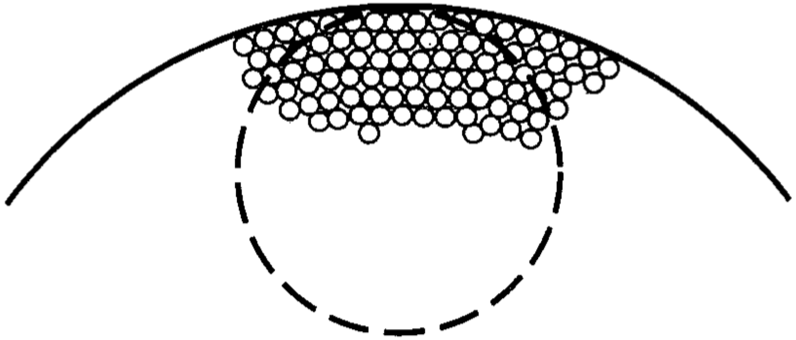
*(*adiabatic – heat does not leave or enter the system – not heat is exchanged between the air parcel and the rest of the air)*

A combination of effects

Kelvin Effect (Curvature Effect)

The vapour pressure over a curved surface is always higher than over a flat surface.

Effect decreases as particle size grows



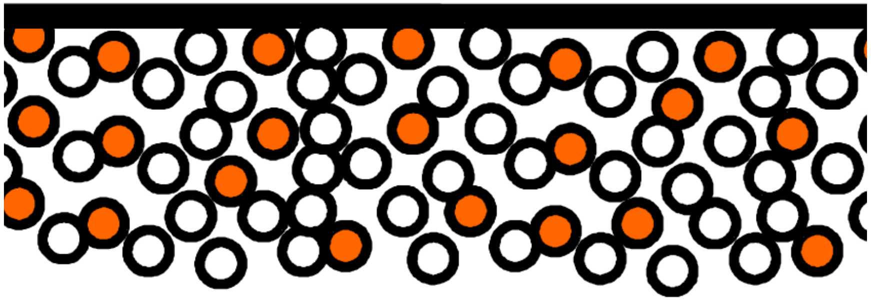
Curvature reduces the number of neighbouring molecules, therefore molecules can escape more *easily*.

Raoult Effect (Solute Effect)

The presence of solute molecules in water *decreases* the vapour pressure.

Decrease in vapour pressure is proportional to the mole fraction of the solute.

Effect decreases as particle size grows



Solute molecules stabilise the systems, making it *harder* for water molecules to escape.

A microphysical approach

UNIVERSITY OF LEEDS

Critical super-saturation

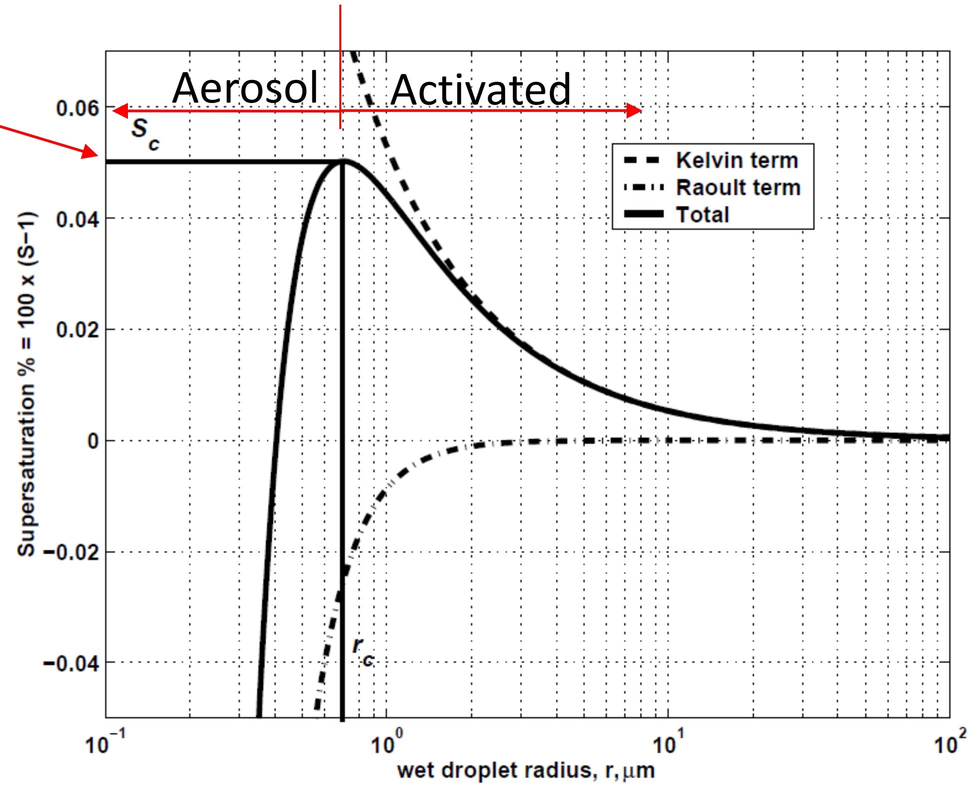


Fig. 1. The Köhler equation can be envisaged as the competition between the curvature (Kelvin) and solute (Raoult) terms.

Activation of a single 200nm dry particle of ammonium sulfate aerosol. McFiggans, ACP, 2012.

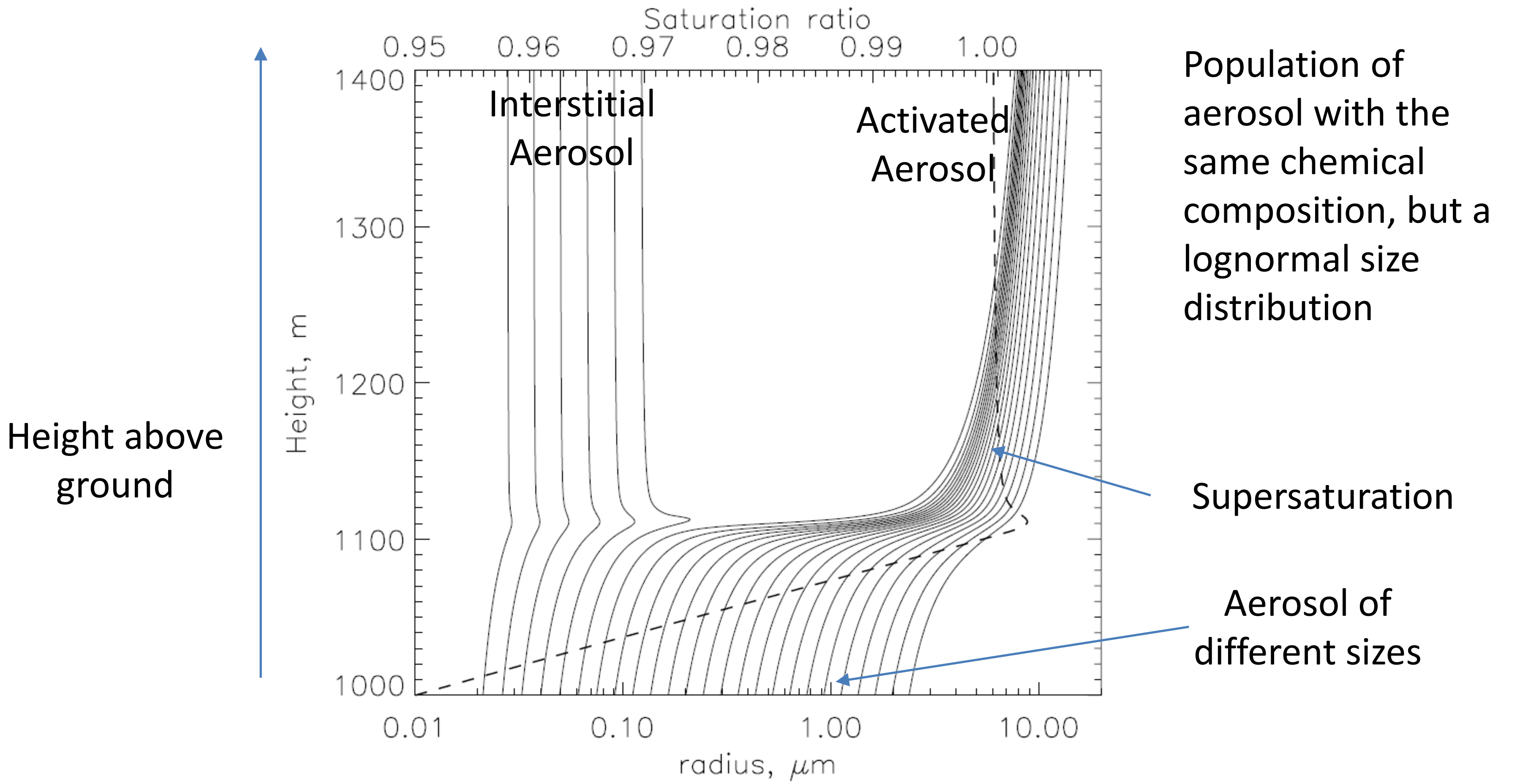
If we know the super-saturation, we can use Kohler theory to calculate whether a particle will be activated or not.

- If the ambient supersaturation is > the critical super-saturation then the droplet can grow and is said to be **activated**.
- Once activated, the droplet will grow further as the more it grows, the smaller the Raoult (curvature) effect.

Growth of an aerosol population.

UNIVERSITY OF LEEDS

McFiggans, ACP, 2012.



Parcel model simulation of the activation of aerosol in a rising air parcel

Microphysical calculation of CDN

Cloud parcel modes are able to predict the changes in supersaturation that occur in a rising air parcel.

The equations governing the distribution of water vapour to a population of aerosol can't be solved analytically.

Need to iterate – fine for a parcel model, but too slow for a global model.

Instead for global models need to do physically based parameterisations that use a mix of Kohler theory and fitting to cloud parcel model results.

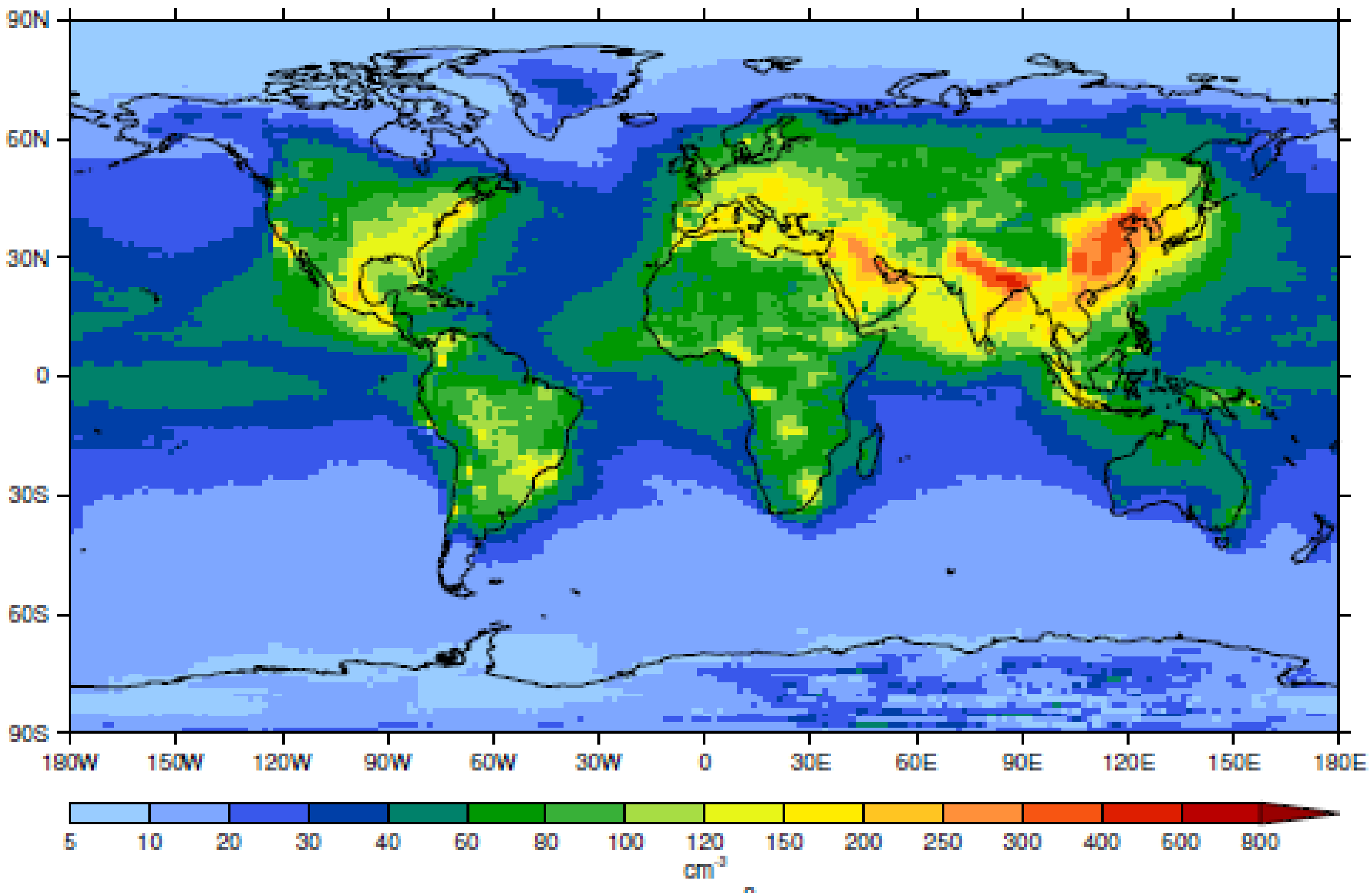
A number of parameterisations available: e.g. Abdul Razzak, Ghan (2010), Nenes and Sienfeld, JGR, 2003.

Calculation of CDN in UKCA

- In the UKCA we calculate cloud droplet number using the parameterisation of Abdul Razzak Ghan (JGR, 2010).
  - Calculates the maximum supersaturation (Smax) achieved in the air parcel following empirical fits to multiple cloud parcel model simulations.
  - GLOMAP-Mode has 4 soluble modes (and 3 insoluble modes). All soluble aerosol modes are allowed to compete for water vapour.
  - Once Smax is known, Kohler theory is used to calculate the critical radius above which activation occurs.
  - Can then calculate what fraction of aerosol in each lognormal mode would activate.
  - CDN is calculated at cloud base and assumed to be constant (in the vertical) throughout a continuous cloud layer
- Scheme implemented and evaluated in UKCA by Rosalind West and Philip Stier, Oxford.

Abdul Razzak and Ghan Scheme

West, R. *et al*, ACP, 2010



Annual mean CDN at Cloud top, assuming PDF of updrafts with sigma=0.4

CDN is calculated at cloud base, and then that value is then used throughout the vertical extent of the cloud.

Updraft (or Vertical) Velocity

UNIVERSITY OF LEEDS

- The in-cloud updraft velocity is the main driving force for expansion / cooling and therefore cloud formation.
- For a given aerosol population, the greater the updraft velocity, the larger the in-cloud super-saturation, and the higher the CDN.
- **BUT! Updraft velocity is very variable, hard to prognose in a large scale model, and relatively hard to measure (*in-situ* measurements).**

Updraft velocity varies between cloud types.

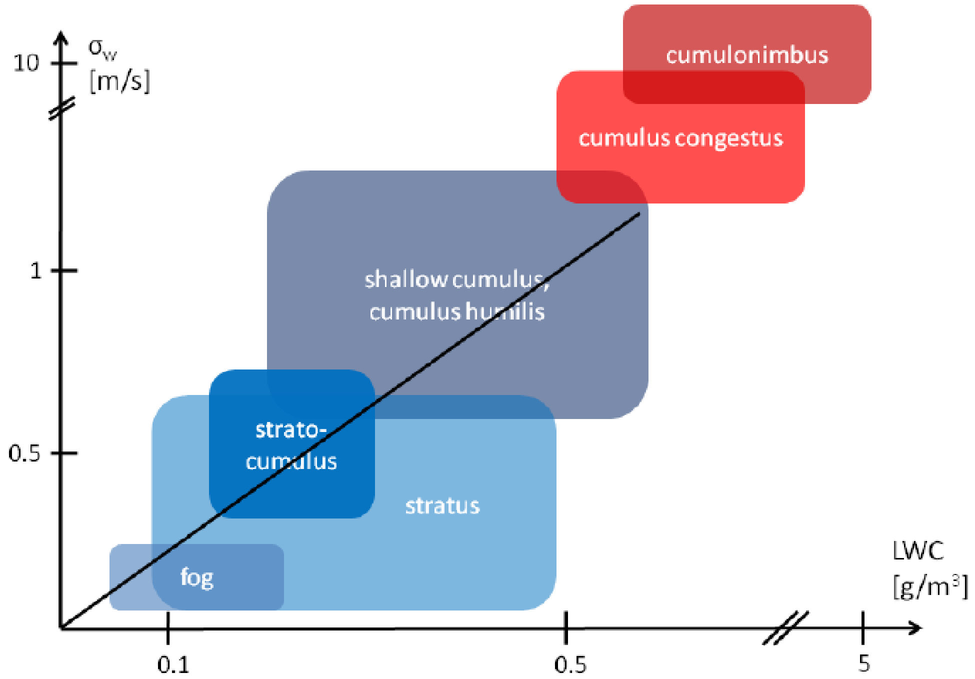


Image from Corrina Hoose (after Cotton and Anthes, 1989)

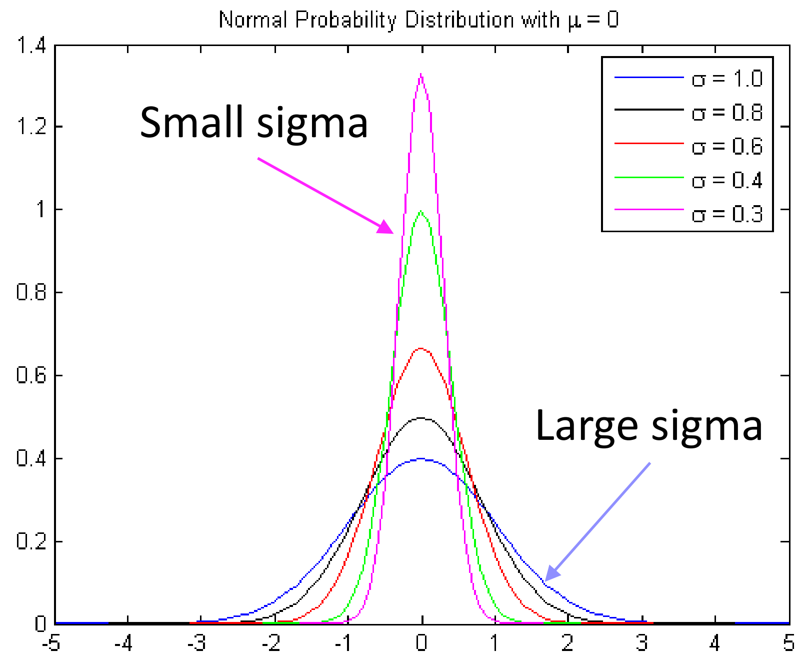
Sub-grid Variations in Updraft (or Vertical) Velocity

UNIVERSITY OF LEEDS

Typically, the large-scale vertical velocities resolved at the GCM grid scale are small; it is the unresolved sub-grid scale fluctuations which give rise to the updrafts associated with cloud formation

Gaussian Approach:

- PDF of updraft velocities (perform multiple calculations, then integrate to get an overall CDN).
- Assume PDF follows a Gaussian distribution centred on zero.
- Only consider updrafts > 0.



How do we know what the “correct” value of sigma is?

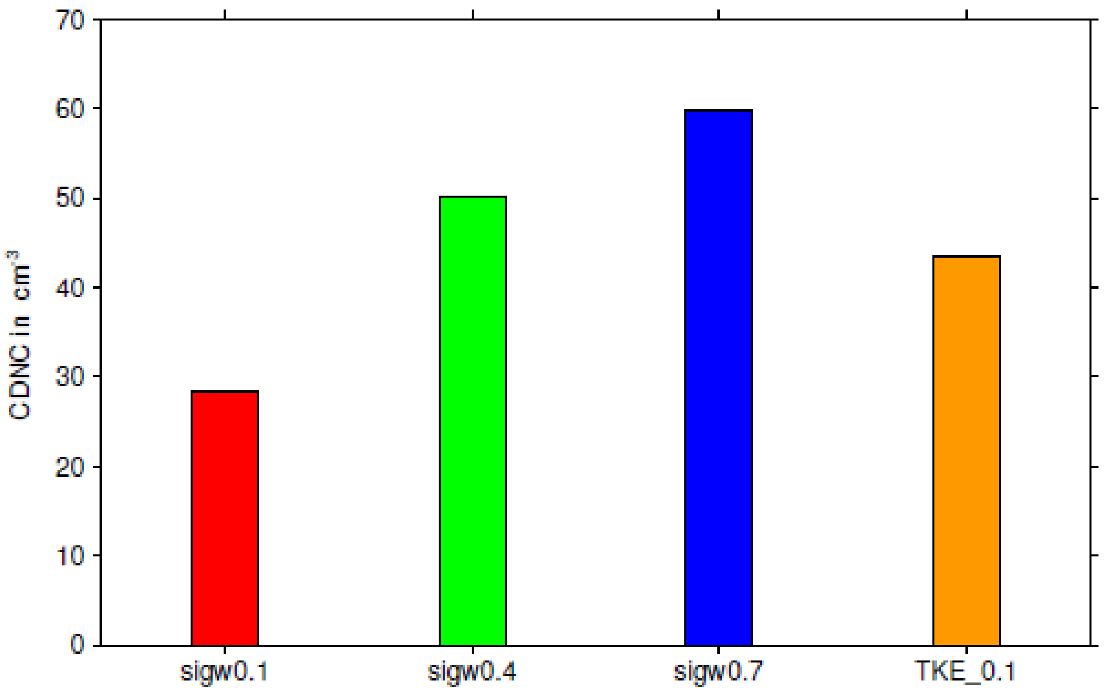
Dependence of CDN on updraft

UNIVERSITY OF LEEDS

West et al, (2014) performed sensitivity simulations with the ARG scheme in the UKCA.

Assumed various global mean values of sigma.

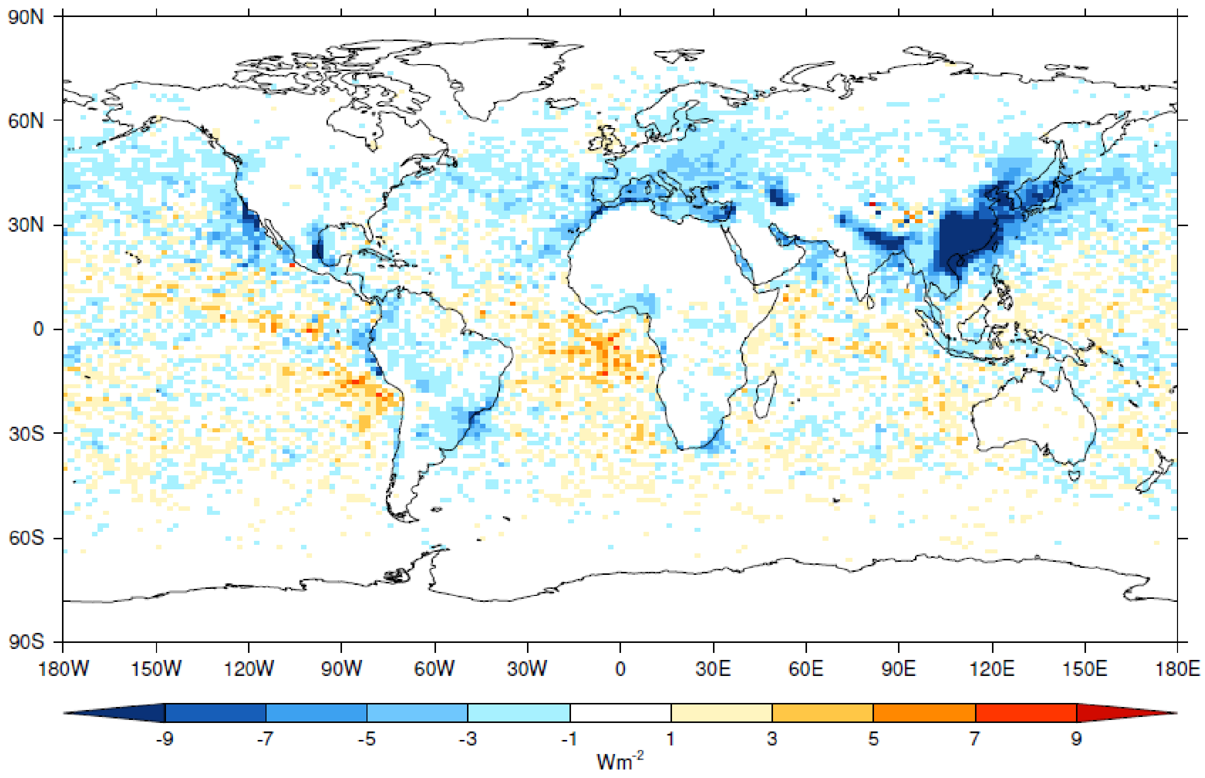
Found that increasing sigma form 0.1 t o 0.7 lead to a doubling of the calculated global mean CDN.



Reference	Standard deviation [m s^{-1}]
sigw0.1	$\sigma_W = 0.1$
sigw0.4	$\sigma_W = 0.4$
sigw0.7	$\sigma_W = 0.7$
TKE_0.1	$\sigma_W = \max\left(\sqrt{\frac{2}{3}\mathrm{TKE}},\ 0.1\right)$

Above the boundary layer turbulent kinetic energy (TKE) is not calculated so a sigma of 0.1 is assumed.

Sensitivity of forcing to updraft velocity



(b) RFP(sigw0.7) – RFP(sigw0.1)

Range of ERFs from -1.9 to -2.3 Wm-2

Implementation in UKCA

UNIVERSITY OF LEEDS

L_UKCA_AIE1=.TRUE.

- CDN is passed down into the radiation scheme and used in the calculation of droplet effective radius in R2_RE_MRF_UMIST.
- There are many layers of forwarding routines, but it's passed through from ATMOS_PHYSICS1 as n_drop_pot!
- This causes the effective radius, and hence the cloud albedo, to depend on the number of activated droplets, giving rise to the first indirect effect.

L_UKCA_AIE2=.TRUE.

- The CDN is passed down into the precipitation scheme (LS_PPN) and used in the calculation of the droplet size distribution (LSP_TAPER_NDROP) used in the autoconversion parameterisation (LSP_AUTOC).
- This causes the autoconversion rate to respond to changes in the number of activated droplets, giving rise to the second indirect effect.

The details of the CDNC dependence can be found in UMDP 26, which describes the large-scale precipitation scheme in great detail.

Isolating different aerosol /cloud interactions

UNIVERSITY OF LEEDS

Single Call

AFaci + Adjustments

L_UKCA_AIE1=.TRUE.
L_UKCA_AIE2=.TRUE.

UKCA_MODE Aerosol

ACTIVATE - CDN

Effective radius calculate using ACTIVATE_CDN

Radiation scheme

Effective radius calculated using default CDN

Radiation scheme

Double Call

(isolate just albedo effect)

AFaci

L_UKCA_AIE1=.TRUE.
L_UKCA_AIE2=.FALSE.

Conclusions

- Human emissions of aerosol particles can affect both cloud brightness and lifetime, which can alter the Earths' radiative budget.
- This is one of the greatest uncertainties in our ability to understand and predict the effect of human activities on climate.
- To treat this in GCM, need a parameterisation of the relationship between the aerosol present and CDN.
- Historically used empirical relationships, which were based on observations of aerosols number (or mass) and CDN.
- Kohler-based parameterisations take the meteorological conditions (temp and pressure) as well as the aerosol size distribution and chemical composition into account to provide a more sophisticated treatment.

Conclusions

UNIVERSITY OF LEEDS

- The activation scheme of Abdul Razzak and Ghan has been implemented and evaluated in the UKCA.
- The ARG scheme, the same as all physically-based schemes, relies on description of in-cloud updraft velocity.
- Currently UKCA assumes a Gaussian distribution of updraft velocities, with sigma parameterised as a function of the TKE. This is a similar level of sophistication to other global models, but an area of uncertainty.
- Using the available switches it is possible to isolate both the AFaci (first aerosol indirect effect) and Afaci + Feedbacks (cloud lifetime) effects.

References

Abdul-Razzak, H. and Ghan, S. J.: A parameterization of aerosol activation 2. Multiple aerosol types, J. Geophys. Res., 105, 6837–6844, URL http://dx.doi.org/10.1029/1999JD901161, 2000.

McFiggans, G., Artaxo, P., Baltensperger, U., Coe, H., Facchini, M. C., Feingold, G., Fuzzi, S., Gysel, M., Laaksonen, A., Lohmann, U., Mentel, T. F., Murphy, D. M., O'Dowd, C. D.,

Snider, J. R., and Weingartner, E.: The effect of physical and chemical aerosol properties on warm cloud droplet activation, Atmos. Chem. Phys., 6, 2593–2649, doi:10.5194/acp-6-2593-2006, URL http://www.atmos-chem-phys.net/6/2593/2006/, 2006.

West, R. E. L.: Estimation of the indirect radiative effects of aerosol on climate using a general circulation model, DPhil thesis, Jesus College, University of Oxford, Oxford, UK, URL http://ora.ox.ac.uk/objects/ora:7415, 2012.

West, R. E. L., Stier, P., Jones, A., Johnson, C. E., Mann, G. W., Bellouin, N., Partridge, D. G., and Kipling, Z.: The importance of vertical velocity variability for estimates of the indirect aerosol effects, Atmos. Chem. Phys., 14, 6369–6393, doi:10.5194/acp-14-6369-2014, URL http://www.atmos-chem-phys.net/14/6369/2014/, 2014.