# Wet Deposition in UKCA

Colin Johnson with thanks to:

Jane Mulcahy, Zak Kipling, Graham Mann, and rest of UKCA team

UKCA training course, January 2017

© Crown copyright   Met Office

Met Office | NERC SCIENCE OF THE ENVIRONMENT

JWCRP – a partnership in weather and climate research

# Outline

- What processes are done from atm_step ?
- Wet deposition of trace gases and aerosols
- Aerosol budget analysis

© Crown copyright Met Office

# Atm_step_4A -simplified

1. Atmos_Physics1
    - Energy correction
    - Cloud/LS precipitation schemes
    - Radiation
    - Gravity wave drag

2. Tracer and dynamics advection

3. Atmos_Physics2
    - Convection
    - Boundary layer
    - Hydrology
    - River routing

4. Diffusion

5. Helmholtz solver

6. Carriolle ozone scheme

7. Tracer conservation

8. Aerosol modelling (CLASSIC)

9. Nudging

10. UKCA

# Wet Deposition

- Wet deposition is an important process for both soluble gas-phase and aerosol tracers, and dominates over the removal rate by dry deposition of highly soluble gas-phase tracers such as nitric acid and most aerosols in the accumulation and Aitken modes

- There are considerable uncertainties caused by uncertainties in both the simulated precipitation fields and in the simplified treatment of wet deposition of the tracers

- See also: UMDP 84, O'Connor et al. (2014) *Geosci. Model Dev.* **7**, 41-91, Mann et al. *Geosci. Model Dev.* **3**, 519-551, and in-line code comments

© Crown copyright Met Office

# Wet Deposition of soluble tracers in UKCA

- Gas-phase: handled in UKCA for both LS (large scale) and convective precipitation
    - Attempt to introduce plume scavenging for gas-phase tracers is in progress

- Soluble aerosol tracers:
    - LS nucleation scavenging is done in UKCA
    - Impaction scavenging is done in UKCA
    - Plume scavenging is called from the convection scheme
    - In-cloud impaction scavenging is not included in the model

- Plume scavenging for aerosol tracers is the default scheme – it is an essential process in GA7 and exclusion of plume scavenging leads to overestimation of aerosol concentrations and AODs

- Recent models include a prognostic rain scheme to avoid excessive "drizzle" caused by the assumption that all rain formed is able to fall out over the timestep.  See D.N.Walters et al. (2011) *Geosci. Mod. Dev.* **4**, 919-941 for a description of the prognostic rain scheme

- Re-evaporation of dissolved tracers in hydrometeors is not yet included

# Gas-phase soluble tracers

- The chemical definition file (e.g. ukca_chem_strattrop) defines the soluble species:

```
chch_t( 10,'HONO2     ',  1,'TR        ','          ',  1,  1,  0),  &!
11 DD: 8,WD: 5,
```

- The fraction of soluble tracer contained in the cloud droplets depends on the effective Henry law coefficient and the cloud liquid water content (kg/m3). The Henry law information is in the same file. Dissolved fraction is also required for aqueous-phase chemistry.

- The effective Henry law coefficient is calculated as:

$$H(\mathrm{eff}) = K(298)\mathrm{exp}\{[-\mathrm{deltaH}/R]\mathrm{x}[(1/T)-(1/298)]\}$$

- Some species dissociate within the droplet, so a second and third set of K(298) and deltaH/R may be needed to calculate H(eff). The dissolved fraction arrays in UKCA have final dimension of 3 to account for this. See Giannakopoulos et al. (1999), *J. Geophys. Res.* (D19) **104**, 23761-23784.

© Crown copyright Met Office

# Gas-phase tracer removal

JWCRP – a partnership in weather and climate research

- Removal rate of the dissolved trace gas is assumed to be proportional to the rainfall rate via an empirical scavenging coefficient
- Gas-phase tracer removal in UKCA is described by O'Connor et al. (2014) *Geosci. Model Dev.* **7**, 41-91. The scheme uses the nitric acid scavenging coefficients for dynamic and convective precipitation taken from Penner et al. (1991) *J. Geophys. Res.* **96**, 959-990. These scavenging coefficients are then scaled by the dissolved fraction of each species.
- The removal rate is equal to the scavenging coefficient times the precipitation rate, where this is composed of diagnosed (LS or convective) rain plus snow.
- LS precipitation is assumed to occupy the entire grid box, but the removal rate is multiplied by a grid fraction for convective removal, currently set at 0.3
- See in routine UKCA_WDEPRT

© Crown copyright Met Office

Met Office | NERC SCIENCE OF THE ENVIRONMENT

JWCRP – a partnership in weather and climate research

# Adding a soluble gas-phase species

- To add a soluble species to a chemical scheme, it must be added as a tracer to the chch_defs array in the chemical setup file, and also be available in the STASHmaster_A file as a section 34 tracer.

- The number of gas-phase tracers (jpctr) and number of soluble tracers (jpdw) is set in routine UKCA_SETUP_CHEM for each chemical scheme

- A Henry law entry for each soluble species must be included in the chemical definition module.

© Crown copyright Met Office

# Evaluation of wet deposition

- To evaluate the wet deposition in UKCA O'Connor et al. (2014) used a 222-Rn radioactive decay experiment with a 210-Pb daughter product in a dual tracer UKCA

- Climatological observations from EML of 210-Pb air concentrations were used to compare with model results, and the wet deposited 210-Pb dataset of Preiss and Genthon (1997) *J. Geophys. Res.* **102**, 25347-25357 was also used in the assessment

- 210-Pb concentrations were in good agreement with the observations at some sites, however UKCA and other models underestimate 210-Pb at the South Pole

- O'Connor et al. (2014) show (Fig. 7) a scatter plot of modelled and measured 210-Pb annual deposition fluxes at a number of sites

© Crown copyright   Met Office

# Wet Deposition of Aerosol Particles

- Aerosol particles may be deposited through:

1. Nucleation scavenging where the particles act as cloud condensation nuclei (CCN) for droplets which then form rain
2. In-cloud impaction scavenging where aerosol particles are collected by impaction with cloud droplets which the form rain (not included in the model)
3. Below-cloud impaction scavenging where aerosol particles are collected by falling precipitation

© Crown copyright Met Office

# Nucleation Scavenging (1)

JWCRP – a partnership in weather and climate research

- Aerosol particles are incorporated into cloud droplets when they act as CCN (activation)

- The scavenging schemes use a simplified approach rather than being coupled to the UKCA activation scheme

- Based on Spracklen et al. (2005) *Atmos. Chem. Phys.* **5**, 2227-2252, soluble particles larger than a critical wet radius are assumed to act as CCN. This radius is a parameter set in routine UKCA_RAINOUT:
  nscavact = 103.0e-9 ! Activation dry radius (n.b. The parameter mode_activation_dryr set in the UKCA namelist in rose edit is used to calculate CCN concentrations)

- This gives the fraction of number and mass in each mode which are dissolved if a cloud is present and become susceptible to wet deposition

© Crown copyright Met Office

# Nucleation Scavenging (2)

- In practise only the Aitken and accumulation modes are affected by the activation radius, as none of the nucleation mode acts as CCN, whereas all of the coarse mode does

- The parameter i_mode_nucscav set in UKCA_OPTION_MOD modifies the scheme outlined above:
    1. Standard scheme with fraction of *insoluble* aerosol mass and number incorporated set to 1 for all modes
    2. Uses the alternative scheme of Steir et al. (2005) *Atmos. Chem. Phys.* **5**, 1125-1126 for ECHAM5-HAM where fixed scavenging fractions for each mode are used: rscav =(/0.10,0.25,0.85,0.99,0.20,0.40,0.40/)
    3. As 1, but with fractions for accumulation and coarse *insoluble* modes set to zero (Recommended setting)

- The aerosol is then removed at the same rate as the cloud water itself is removed as precipitation based on diagnostics from the LS precipitation scheme (UMDP 26)

© Crown copyright Met Office

# Nucleation Scavenging (3)

JWCRP – a partnership in weather and climate research

- Removal of cloud water is the sum of autoconversion (PRAUT) , accretion by rain (PRACW), and riming by ice/snow (PIACW/PSACW)
- These are added together in UKCA_AERO_CTL before being passed to the aerosol nucleation scavenging routine (UKCA_RAINOUT)
- The removal rate is multiplied by the liquid cloud fraction and by an assumed fraction of the raining portion of the cloud (0.3)
- For very low liquid water contents, a fixed removal timescale is applied instead
- Below 258 K, all insoluble modes are also susceptible to wet deposition (but by rain only – there is no treatment of ice nucleation scavenging)

© Crown copyright Met Office

# Scavenging in the Convective Plume (1)

Met Office | NERC SCIENCE OF THE ENVIRONMENT
JWCRP – a partnership in weather and climate research

- Removal by wet scavenging is required to be linked in with the convective uplift otherwise the convection scheme lifts too much aerosol into the upper part of the model which would result in unrealistic aerosol burdens and AODs

- The treatment of plume scavenging follows Kipling et al. (2013) *Atmos. Chem. Phys.* **13**, 5969-5986 with wet removal done at the same time as convective uplift. See UMDP 27 for a description of the UM convection scheme – recent developments to plume scavenging apply only to the 6A scheme, though the 5A scheme may also be used

- The routine UKCA_PLUME_SCAV (in UKCA_SCAVENGING_MOD) is called from CONVEC2 which is itself called from each of the convective categories

- The fraction of Aitken mode aerosol is not calculated from an activation radius, but is specified in the UKCA namelist as a fraction (*mode_aitsol_cvscav*)

© Crown copyright Met Office

# Scavenging in the Convective Plume (2)

- The entire UM tracer array is passed to UKCA_PLUME_SCAV, and logic is required to identify the relevant tracers (with the StratTrop chemistry scheme, a bug was identified due to $H_2O$ being labelled as a tracer – *only vn10.6 results are valid in this case*). The routine UKCA_SET_CONV_INDICES identifies which tracers to use

- Scavenging coefficients are set in routine UKCA_MODE_SCAVCOEFF and are set to 1.0 for accumulation and coarse modes; to mode_aitsol_cvscav for the Aitken mode; and to zero for all other modes (*i_mode_nucscav = 1 or 3*)

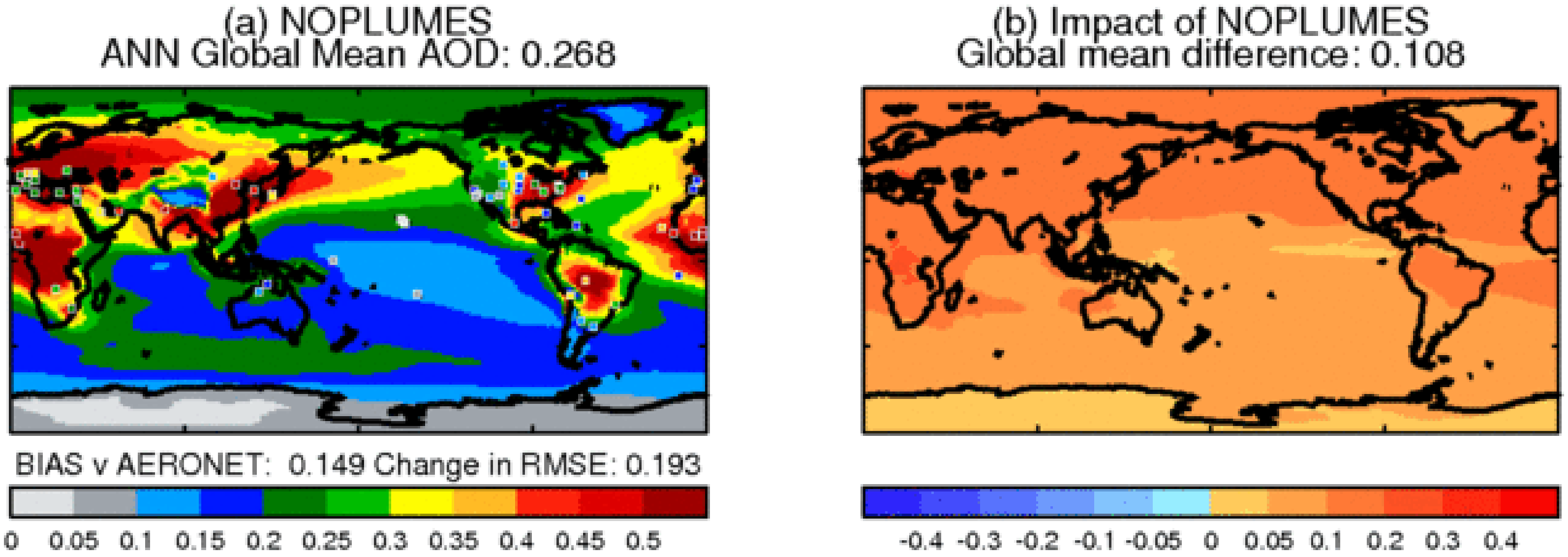
- An alternative set of scavenging coefficients (Stier et al., 2005) may be used by setting *i_mode_nucscav = 2*, this set have non-zero coefficients for all modes

- The diagnostics for plume scavenging are based on the differences in column tracer amounts before and after the convection scheme, so these diagnostics are only available as 2-dimensional quantities. See routines in UKCA_SCAVENGING_DIAGS_MOD

© Crown copyright Met Office

JWCRP – a partnership in weather and climate research

# Impact of Plume scavenging on AOD



(a) NOPLUMES
ANN Global Mean AOD: 0.268

BIAS v AERONET: 0.149 Change in RMSE: 0.193

(b) Impact of NOPLUMES
Global mean difference: 0.108

© Crown copyright Met Office

Met Office NERC SCIENCE OF THE ENVIRONMENT

JWCRP – a partnership in weather and climate research

# Below-Cloud Impaction Scavenging: Rain

- The scheme generally follows Slinn (1984) , but see also the in-line comments in the module: UKCA_IMPC_SCAV, and is based on lookup tables of collection efficiencies for different aerosol and raindrop sizes, where raindrop sizes are distributed into 7 bins using the Marshall-Palmer distribution
- Aerosol modes are treated as monodisperse at their geometric mean wet radius
- The collection efficiencies are set up in UKCA_MODE_IMSCAVCOFF, contained in the UKCA_IMP_SCAV module
- Set l_fix_ukca_impscav (in short term logicals namelist) to be true for bug fixed version

© Crown copyright Met Office

# Below-Cloud Impaction Scavenging: Snow

- The implementation follows Wang et al. (2011) *Atmos. Chem. Phys.* **11**, 12453-12473, and the fraction removed is a power law with coefficients that are prescribed for each mode:

  $$Km = Am \,.\, P^{(Bm)},$$

  where Am and Bm are prescribed coefficients, and P is the total (LS + convective) snowfall rate

- The coefficients used by Wang et al. (2011) for coarse mode aerosols were found to be too large, and have been reduced

© Crown copyright Met Office

Met Office | NERC SCIENCE OF THE ENVIRONMENT

JWCRP – a partnership in weather and climate research

# Evaluation of aerosol scavenging

- Kipling et al. (2013) compared a version of the UKCA model without plume scavenging to a version containing plume scavenging and compared the black carbon aerosol with measurements made in the HIPPO campaign by Wofsy et al. (2011) *Phil. Trans. Roy. Soc.* **A 369**, 2073-2086

- Both the simulated black carbon burden and its vertical distribution were shown to improve against the observations when plume scavenging was included

© Crown copyright Met Office

# Caveats and future developments

- Re-evaporation of dissolved material (gas-phase and aerosols) is not yet included
- Plume scavenging is being extended to treat soluble gas-phase species
- Better treatments and diagnostics are needed to describe the sub-grid scale
- Treatment of the removal by frozen precipitation needs improvement
- Removal of aerosols and trace gases from the atmosphere via wet deposition is a very important process, and uncertainties may be due to: 1) the precipitation fields provided by the atmosphere; 2) parameter uncertainty; or 3) defects in the model scientific process description

© Crown copyright   Met Office

Met Office | NERC SCIENCE OF THE ENVIRONMENT

JWCRP – a partnership in weather and climate research

# Aerosol Budget Analysis

- All significant aerosol processes have associated mass flux diagnostics, these are mainly 3-dimensional, but are 2-dimensional for plume scavenging

- Analysis of these fluxes following model changes can reveal the feedbacks which occur

- A file of the relevant diagnostics for the 5-mode SO4, BC, OC, SS setup has been made available along with IDL analysis scripts, see:

- ARCHER: /work/n02/n02/ukca/Tutorial/AerosolBudget
- MONSooN: /projects/ukca-admin/Tutorial/AerosolBudget
- JASMIN: /group-workspaces/jasmin2/ukca/vol1/Tutorial/AerosolBudget

© Crown copyright Met Office

# Accumulation mode sulphate annual production (Tg(S)/yr) for u-ae684

| Primary emissions | 0.95 | |
|---|---|---|
| In-cloud oxidation of SO2 by O3 | 20.6 | |
| In-cloud oxidation of SO2 by H2O2 | 7.0 | |
| Cloud processing of Aitken-sol | 3.2 | |
| Condensation of H2SO4 | 6.7 | |
| Coagulation of nucleation-sol | 0.1 | |
| Coagulation of Aitken-sol | 0.8 | |
| Mode-merging of Aitken-sol | 1.3 | |
| | | |
| Total incoming mass | 40.7 | |
| | | |

© Crown copyright Met Office

Met Office | NERC SCIENCE OF THE ENVIRONMENT

JWCRP – a partnership in weather and climate research

# Accumulation mode sulphate annual loss (Tg(S)/yr) and loss lifetimes (days)

| Dry deposition | 4.7 | 35.9 |
|---|---|---|
| Nucleation scavenging | 16.3 | 10.3 |
| Plume scavenging | 16.4 | 10.3 |
| Impaction scavenging | 3.2 | 52 |
| Coagulation to coarse-sol | 0.009 | |
| Mode-merging to coarse-sol | 0.37 | |
| Total outgoing mass | 40.9 | 4.1 |
| | | |
| Imbalance (%) | 0.61 | |
| Burden (Tg) | 0.46 | |

© Crown copyright Met Office