Dry Deposition in UKCA

David Stevenson & Federico Centoni
(dstevens@staffmail.ed.ac.uk)
The University of Edinburgh

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http://macaqueedinburgh.wordpress.com/
MACAQUE: Modelling and measuring Atmospheric Composition and Air QUality at Edinburgh
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Outline

• What is dry deposition?
• Why is it interesting/important?
• How is it represented in UKCA?
• Model improvements underway/planned
• Research questions related to dry deposition
What is dry deposition?

- Removal of gases and aerosols by turbulent transfer and uptake at the Earth’s surface
- Process operates on air in boundary layer
- Important sink for many species (O$_3$, H$_2$O$_2$, NO$_2$, PAN, HNO$_3$, NH$_3$, aerosols, CH$_4$, H$_2$, CO, ...)
- Controlled by: BL characteristics – depth, turbulence, diffusion, surface properties (vegetation – stomata, leaf area),...
- Strictly: surface-atmosphere exchange – reverse process operates for some species under some conditions (e.g. NH$_3$)
Annual mean O$_3$ deposition flux
(Year 2000, UKCA vn7.3)
Sources/sinks of tropospheric ozone (yr 2000)

Stratosphere

Troposphere

Chemical production

NO → NO₂ → OH, HO₂, RO₂ → Sunlight → O₃

NMHCs, CO, CH₄ → Emissions

Deposition

Emissions

OH → NO → NO₂ → O₃

Chemical loss

Tropopause ~8–15 km

Stratosphere/Troposphere

Exchange 600 Tg/yr

4600 Tg/yr

Burden: 340 Tg

Lifetime: 22 days

Stevenson et al 2006; Royal Society, 2008
O$_3$ dry deposition ‘velocities’ in the HTAP models

**Figure 3.** Normalised average monthly O$_3$ dry deposition at grid cells with 100% land cover class coverage. Model fluxes are shown in grey and the ensemble average in red.  
Hardacre et al. (2014)
O$_3$ deposition to different land-cover types

Olson Land-cover classes:
- SI: Snow/Ice
- DF: Deciduous Forest
- CF: Coniferous Forest
- AC: Agricultural Land, Crops
- GL: Grass Land
- TF: Tropical Forest
- TN: Tundra
- DT: Desert
- WL: Wetland
- WT: Water

Figure 4. Normalised O$_3$ dry deposition partitioned to land cover classes using the OW11 (a, c) and GCLF (b, d) LCCs respectively. Upper panels show the contribution of each LCC to the annual global O$_3$ dry deposition flux, and lower panels show the average flux to each LCC. The box and whiskers for each land class represent the median, quartiles and 10th/90th percentiles.

Hardacre et al. (2014)
Resistance analogy/deposition velocity
(‘Wesely-type schemes’, e.g., Wesely, 1989)

Consider three ‘resistances’ in series:
- $R_a$: Aerodynamic resistance
  *Depends on surface type*
- $R_b$: Boundary layer resistance
  (‘quasi-laminar sub-layer resistance’)
  *Depends on species (diffusion coefficient)*
- $R_c$: Canopy (/surface) resistance
  *Depends on surface type & species*

Deposition velocity:
$$V_d = \frac{1}{R_a + R_b + R_c}$$
= Flux/Concentration (at ref ht)
= [kg m$^{-2}$ s$^{-1}$] / [kg m$^{-3}$] = m s$^{-1}$

(Analogy:
Flux ≡ Current; Concentration ≡ Voltage;
Voltage = Current x Resistance, $V=IR$)

Earth’s surface
Expanded surface/canopy resistance terms

Surface resistances: Ice/Soil/Water/Urban

Canopy (vegetation) resistances

Federico Centoni, after Wesely (1989)
Aside: \( \text{O}_3 \) impacts via deposition
Ozone damages plants

Ozone enters a plant via stomata; attacks plant cells
Ozone damages crops

O$_3$ injury to wheat, Pakistan (courtesy of A. Wahid)
O$_3$ impacts on vegetation

‘FACE’ experiments (Free Air CO$_2$ enrichment)
Also ozone – see http://aspenface.mtu.edu
Ozone impacts at ambient levels (~40 ppb)

Ozone impacts at elevated levels (~80-100 ppb)
Indirect O$_3$ radiative forcing, via reduced C-sequestration

\[ \sim \text{doubles O}_3 \text{ RF} \]

Sitch et al. (2007)
Expanded surface/canopy resistance terms

Surface resistances: Ice/Soil/Water/Urban

Canopy (vegetation) resistances

Federico Centoni, after Wesely (1989)
Aerodynamic resistance: $R_a$

- Depends on BL stability (heat flux), surface roughness, friction velocity, etc.

$$R_a = \left( \ln \left( \frac{Z}{z_0} \right) - \varphi \right) / k u_*$$

- Varies with surface type (use ‘tile’ approach), but independent of species
- UKCA subroutine: `ukca_aerod.F90`
Tile approach for land cover

- Each grid square is assigned a fraction of nine different surface types, based on land-cover mapping, e.g.:

Overall grid properties calculated based on combination of different tile fractions. No sub-grid-scale spatial distribution information, just fractions.

(Other surface types: Broadleaf trees, shrubs, C4 grass, ice, bare soil)
Quasi-laminar sub-layer resistance: $R_b$

- Depends on diffusion coefficient of species, friction velocity, etc.

$$R_b = \left(\frac{Sc}{Pr}\right)^{2/3} / ku_*$$

Sc: Schmidt number (diffusion vs viscosity)
Pr: Prandtl number (0.72 for lower atmosphere)

- Varies with species diffusivity, independent of surface

- UKCA subroutine: ukca_aerod.F90
Surface/canopy resistance: $R_c$

- Multiple influences, dependent on surface type, species, environmental conditions...
- Non-vegetated surfaces: water, ice, soil, urban
- Vegetated surfaces:
  - Canopy structure (e.g., grass vs. forest)
  - Stomatal uptake
    - Soil moisture, time of day
  - Non-stomatal (leaf cuticle/stem uptake)
    - Leaf Area Index (LAI = leaf surface area/land area)
- UKCA subroutine: `ukca_surfddr.F90`
Dry deposition in UKCA

- **ukca_chemistry_ctl**
- **ukca_ddepctl**
  - loss rate \([s^{-1}]\): \(zdryrt\) (lon, lat, species)
  - # levels in BL: \(nlev\_in\_bl\) (lon, lat)
- **ukca_aerod**
  - \(R_a\) (lon, lat, surface type)
  - \(R_b\) (lon, lat, species)
- **ukca_surfddr**
  - \(R_c\) (lon, lat, surface type, species)
  - Combine \(R_a, R_b, R_c\) to get \(V_d\) (lon, lat, surface type, species)
  - Combine \(V_d\) across surface types to get \(zdryrt\) (lon, lat, species)
  - # levels in BL: \(nlev\_in\_bl\) (lon, lat)
- **ukca_ddcalc**
- **ukca_be_drydep**
- **asad_cdrive**
  - Backward-Euler specific version of \(zdryrt\)
  - Loss rate from dry deposition integrated into all production/loss processes for each species
Table 16: Species treated by the interactive dry deposition scheme.

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Formula</th>
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<td>NO₂</td>
</tr>
<tr>
<td>NO₃</td>
<td>NO₃</td>
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<td>H₂SO₄</td>
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<td>CH₃OOH</td>
<td>CH₃OOH</td>
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<tr>
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<tr>
<td>ROOH</td>
<td>Other organic peroxides</td>
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<tr>
<td>PAN</td>
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<tr>
<td>PPN</td>
<td></td>
</tr>
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<td>OnitU</td>
<td></td>
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<tr>
<td>SEC_ORG</td>
<td>Any other secondary organics</td>
</tr>
<tr>
<td>ORGNIT</td>
<td>Organic nitrogen</td>
</tr>
</tbody>
</table>

Examples to follow focus on ozone, but NB many species dry deposited

Abraham et al. (2012)
Bug fix 1: Stomatal conductance

- Stomatal conductance ($g_{sto}$) currently erroneously contains a (non-diurnally varying) soil conductance term, so it exhibits the wrong diurnal cycle – important where stomatal uptake is a major term in $R_c$.

Diurnal cycles of stomatal conductance over southern Scotland for different seasons

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Error most prominent at night / winter
Global impact of the stomatal bug fix

$\Delta O_3$ deposition velocity (%)  (Jan)

$\Delta O_3$ deposition flux (%)  (Jan)

$\Delta O_3$ surface concentration (%)  (Jan)

$\Delta O_3$ surface concentration (ppb)  (Jan)

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Bug fix 2: In-canopy resistance

In the current UKCA versions, the in-canopy resistance term ($R_{ac}$) is missing (i.e. zero) everywhere!
Global impact of the $R_{ac}$ bug fix

Adding the resistance term reduces deposition, particularly over forests, so $O_3$ concentrations increase.

[Caveat: I am unsure if $R_{ac}$ terms still need to be added for all species: I think here only the $O_3$ $R_{ac}$ terms have been added; this is probably important.]
Further code developments: Zhang et al. (2003)
Impacts of Zhang et al scheme on O$_3$ deposition flux & surface O$_3$ concentration

Currently evaluating whether the Zhang scheme improves comparisons with observations
Modelling dry deposition: How do we formulate models?

Deposit from multiple levels

Deposit from single surface level only

Top of boundary layer

Model grid boxes

BL mixing
BL chemistry
Deposition

Over 30 minute model time-step, ~whole BL ‘sees’ surface...

But all deposited gases must pass through lowest layer...

(Current UKCA set-up)

(Most other models)
Both sorts of schemes implemented in UKCA model

% change in $O_3$ dep flux, single level scheme minus multi-level scheme (July monthly mean)

Global total $O_3$ dep flux remains at $\sim$1100 Tg/yr

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Big differences in simulated surface $\text{O}_3$...

Change in $\text{O}_3$ (ppb), single level scheme minus multi-level scheme
(July monthly mean)

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Future research questions related to dry deposition

• Evaluation of more sophisticated process-based schemes – do they actually improve things?
• Sensitivity to climate change/land-cover change
  – Do the new schemes change this?
  – Stomatal vs non-stomatal partitioning (crops/RF)
  – Impacts beyond ozone (e.g. N-dep)
  – Behaviour during extreme events (e.g. heatwaves)
  – Past as well as future (e.g. $O_3$ trends)
• Integration of ‘surface exchange’ (deposition and emissions; also BL mixing) processes
Summary

• Most of the fixes/changes implemented in the deposition scheme induce large changes in surface level ozone
  – Reminds us that the way dry deposition is represented in models has a large impact on results
  – Dry deposition is a large source of uncertainty
• Focussed on ozone, but deposition also very important for aerosols (e.g., BC) and other species
• Plenty of work still to do (evaluation, further development, climate change impacts, etc.)