Dry Deposition in UKCA – What Is It? How Does It Work?

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Acknowledgements

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Agenda

1.) What Is Dry Deposition?
2.) What Makes It Important (Why Do We Care)?
3.) How Is It Represented In UKCA
4.) Applications In Research
5.) Current And Future Developments

Take-home Ideas

Questions?!? (and answers ...)
What Is Dry Deposition?

- Removal of gases/aerosols by turbulent transfer and uptake at the Earth’s surface
- Important sink for atmospheric trace gases ($O_3$, $HNO_3$, $NH_3$, PM, $CH_4$, CO)
- Depends on PBL (depth, turbulence, diffusion) and surface structure (surface type, ecosystem productivity, season)
- Strictly speaking, not a one-way flux. Rather: surface-atmosphere exchange – a reverse flow may occur for some species under some conditions, e.g., $NH_3$
O$_3$ Sources & Sinks (yr 2000)

Stevenson et al., JGR, 111, D08301, 2006; Royal Society, 2008.
The “Standard Model”

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:

$$V_d = 1/(R_a + R_b + R_c)$$

= Flux/Concentration (at reference height)

= $[\text{kg m}^{-2} \text{s}^{-1}] / [\text{kg m}^{-3}] = \text{m s}^{-1}$; $[R_i] = \text{s m}^{-1}$

Analogy: Flux $\equiv$ Current
Concentration $\equiv$ Voltage
Voltage = Current x Resistance $\rightarrow$
$1/R = I/V$

O$_3$ Deposition In Models (HTAP)

**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.
O₃ Deposition Measurements

At A Tropical Rain Forest in Southwest Amazonia

Rummel et al., ACP, 7, 5415-5435, 2007.
Model-to-Obs Comparison

$5.0 \cdot 10^{-10} \text{ kg m}^{-2} \text{ s}^{-1} = 10.4 \text{ nmol m}^{-2} \text{ s}^{-1}$

Hardacre et al., ACP, 15, 6419-6436, 2015.

Rummel et al., ACP, 7, 5415-5435, 2007.
Different Land-Cover Classes

Olson land-cover classes:

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

Figure 4. Normalised O₃ 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 O₃ 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.
Importance Of Dry Deposition

• Efficient Removal Process
  • gas-phase species
    • most important for ozone
    • many organic compounds
      • aldehydes, ketones, alcohols, hydroperoxides
    • organic compounds with nitrogen
      • e.g., PAN and other nitrates
  • particulate matter (aerosols)
    • fine and ultra-fine aerosols
    • black carbon aerosol (soot)
    • organic carbon aerosol

1 not the same as sedimentation which is dominated by gravity and affects coarse aerosols predominantly
Importance Of O$_3$-Deposition

- Mechanism
  - leaf-internal cell damages
    - reddening, necrosis
  - reduced photosynthetic rates
  - accelerated leaf senescence

- Economic Impacts
  - reduced crop yields
  - global economic losses*
    - $14 - $26 billion annually
  - implications for food security

O$_3$-Impacts On Vegetation

Present-day and Future Ozone Impacts

O$_3$ impacts at ambient levels (~40 ppbv) vs. O$_3$ impacts at elevated levels (80-100 ppbv)

Leaves most affected

Its Representation In UKCA

Table 16: Species treated by the interactive dry deposition scheme.

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>O3</td>
<td>O₃</td>
</tr>
<tr>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>NO₂</td>
<td>NO₂</td>
</tr>
<tr>
<td>NO₃</td>
<td>NO₃</td>
</tr>
<tr>
<td>N₂O₅</td>
<td>N₂O₅</td>
</tr>
<tr>
<td>HONO2</td>
<td>HNO₃</td>
</tr>
<tr>
<td>HONO</td>
<td>HONO</td>
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<tr>
<td>ISON</td>
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<td>H₂SO₄</td>
<td>H₂O₄</td>
</tr>
<tr>
<td>H₂O₂</td>
<td>H₂O₂</td>
</tr>
<tr>
<td>H₂</td>
<td>H₂</td>
</tr>
<tr>
<td>CH₃OOH</td>
<td>CH₃OOH</td>
</tr>
<tr>
<td>HACET</td>
<td></td>
</tr>
<tr>
<td>ROOH</td>
<td>Other organic peroxides</td>
</tr>
<tr>
<td>PAN</td>
<td></td>
</tr>
<tr>
<td>PPAN</td>
<td></td>
</tr>
<tr>
<td>MPAN</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>CO</td>
</tr>
<tr>
<td>CH₄</td>
<td>CH₄</td>
</tr>
<tr>
<td>NH₃</td>
<td>NH₃</td>
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<td>H₂</td>
<td>H₂</td>
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<tr>
<td>SO₂</td>
<td>SO₂</td>
</tr>
<tr>
<td>DMSO</td>
<td></td>
</tr>
<tr>
<td>MSA</td>
<td></td>
</tr>
<tr>
<td>OnitU</td>
<td></td>
</tr>
<tr>
<td>SEC_ORG</td>
<td>Any other secondary organics</td>
</tr>
<tr>
<td>ORGNIT</td>
<td>Organic nitrogen</td>
</tr>
</tbody>
</table>

- many species subject to dry deposition
  - solubility mostly good indicator
- dry deposition of gaseous and aerosol species treated independently
  - **Gas-phase species:**
    Use resistance-in-series approach (Wesely/Zhang)
  - **Aerosol species:**
    Use roughness length to infer surface type and then use prescribed velocities.
Subgrid Surface Properties

- standard configuration: 9-tile/5-PFT
  - broadleaf trees, needle-leaf trees, C3 and C4 grasses, shrubs, urban, bare soil, water and ice
- gridbox surface property = tile-weighted sum of all tile properties
- further configurations exist
  - 13-tile/9-PFT configuration
    - more PFTs; same number of non-PFT tiles
  - 17-tile/13-PFT configuration
    - four additional crop tiles
  - 27-tile/13-PFT configuration
    - more ice tiles
- number and nature of tiles determined by configuration, not by code
  - no code changes when using alternative setup
UKCA Calling Diagram

**calling-level routines**

- `ukca_chemistry_ctl.F90`
- `ukca_chemistry_ctl_BE.F90`
- `ukca_ddepctl.F90`
- `ukca_aerod.F90`
- `ukca_surfdr.F90`
- `ukca_ddcalc.F90`
- `ukca_be_drydep.F90`
- `asad_cdrive.F90`

**loss rate [s⁻¹]:** `zdryrt(lon, lat, species)`

# levels in BL: `nlev_in_bl(lon, lat)`

- **R_a (lon, lat, surface type)**
- **R_b (lon, lat, species)**
- **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)`

assign constant loss rates [s⁻¹]

(only special circumstances)
**Ra and Rb Terms**

**Aerodynamic resistance:**

\[ R_a = \frac{\ln\left(\frac{z}{z_0}\right) - \varphi}{ku^*} \]

- depends on BL stability, surface roughness, friction velocity
- varies with surface type
- independent of species
- UKCA subroutine: `ukca_aerod.F90`

**Quasi-laminar sub-layer resistance:**

\[ R_b = \left(\frac{Sc}{Pr}\right)^{2/3} \frac{1}{ku^*} \]

- depends on diffusion coefficient, friction velocity
- independent of surface type
- varies with species
- UKCA subroutine: `ukca_aerod.F90`

*Sc: Schmidt Number (diffusion vs. viscosity)*
*Pr: Prandtl Number (0.72 for lower atmosphere)*
Canopy/Surface Resistance $R_c$

- dependent on surface type, species, environmental conditions, etc.
- non-vegetated surfaces
  - water, ice, bare soil, urban
- vegetated surfaces (canopy structure, e.g., grass vs. forest)
  - stomatal uptake
  - soil moisture
  - time of day
  - leaf cuticle/stem uptake
  - leaf area
- UKCA subroutine: `ukca_surfddr.F90`
Application in Research

- O₃-dry deposition related indirect radiative forcing (RF)
  - reduced ecosystem productivity
  - diminished carbon assimilation
  - decreased terrestrial carbon sink
  - increased CO₂ burden in atmosphere
  - additional radiative forcing
- Increased RF by 2100
  - 0.62 W m⁻² to 1.09 W m⁻²
  - c.f., direct O₃ RF: 0.89 W m⁻²
O$_3$-Dry Deposition in Ecosystems

[Map of South America showing distribution of Broadleaf Trees and C3 Grasses]

September

$[O_3]$ (ppb)

$\Delta NPP$ (%)

- 230 TgC yr$^{-1}$ – Same Magnitude as CO$_2$ Release from Fires

Selected Recent Work

- **Coupling to Ecosystems**
  - *Federico Centoni and David Stevenson*
    - missing in-canopy $R_{ca}$ & $R_{cut}$ terms
    - disentangle stomatal from soil resistance term
  - *Maria Val Martin et al.*
    - coupling to vegetation phenology (GRL, 10.1002/2014GL059651, 2014)

- **Oceanic Ozone Deposition**
  - *Catherine Hardacre et al.*
    - $O_3$ dry deposition evaluation in global models (ACP, 15, 6419-6436, 2015)
      - oceanic ozone deposition dominant
  - *Ashok Luhar et al.*
    - evaluation of oceanic ozone deposition schemes (ACP, 17, 3749-3767, 2017)
      - 2-4 times overestimation of deposition velocity
Future Developments

• tighter coupling to the ecosystems
  • Increase consistency between UKCA and JULES
    • More land surface types; emphasis on oceans and the cryosphere
    • consider 3D-canopy deposition model
• move towards more process-based dry deposition schemes
• shift towards ‘bidirectional surface exchange’ schemes: deposition, (re-)emission and PBL mixing
  • closure of the N-cycle (towards a fully coupled atmosphere-land surface scheme)
• designing a new framework for modelling dry deposition
  • where should dry deposition ‘live’?
Research Questions

• 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
  • impacts beyond ozone (e.g. N-dep)
  • behaviour during extreme events (e.g. heatwaves)
  • past as well as future (e.g. $O_3$ trends)
Dry Deposition Working Group

• Dry deposition working group formed as part of the NERC ACITES* project

• Informal meetings held at JULES (2013) and ACITES (2014, 2015) events

• New members welcome

• Subgroup created to consider future ESM developments:
  – G. Hayman, E. Nemitz (CEH)
  – O. Wild (U. Lancaster)
  – J. Mulcahy, F. O’Connor, A. Hewitt, A. Wilshire, G. Folberth (Met Office)
  – L. Emberson (SEI, York)
  – D. Stevenson (U. Edinburgh)
  – N. L. Abraham (U. Cambridge)

(*) ACITES = Atmospheric Chemistry in the Earth System
https://www.ncas.ac.uk/index.php/en/acites-news
Three Ideas You Want to Keep:

- Dry deposition of gaseous species and particulate matter (aerosols) constitutes a major atmospheric removal process.

- It is tightly linked to the global plant ecosystems and their functioning in the Earth System.

- Earth System Models are Created to Integrate the Process Understanding and Study the Emerging System Properties.
Q&A and Discussions...