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

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- Luke Abraham (University of Cambridge)
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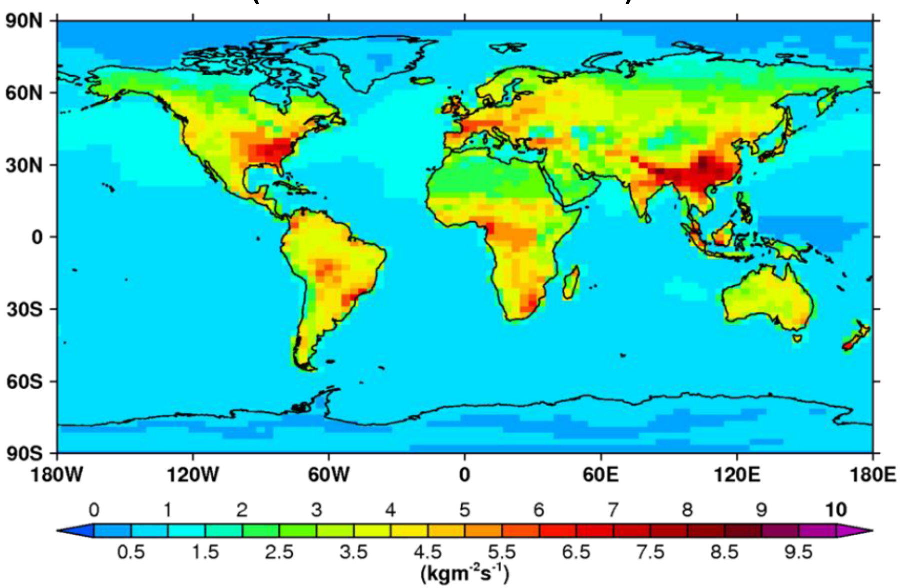
- Mike Sanderson (UK Met Office)
- Oliver Wild (University of Lancaster)

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?

Global Annual Mean O_3 Deposition Flux
(Year 2000 – UKCA vn7.3)



- 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

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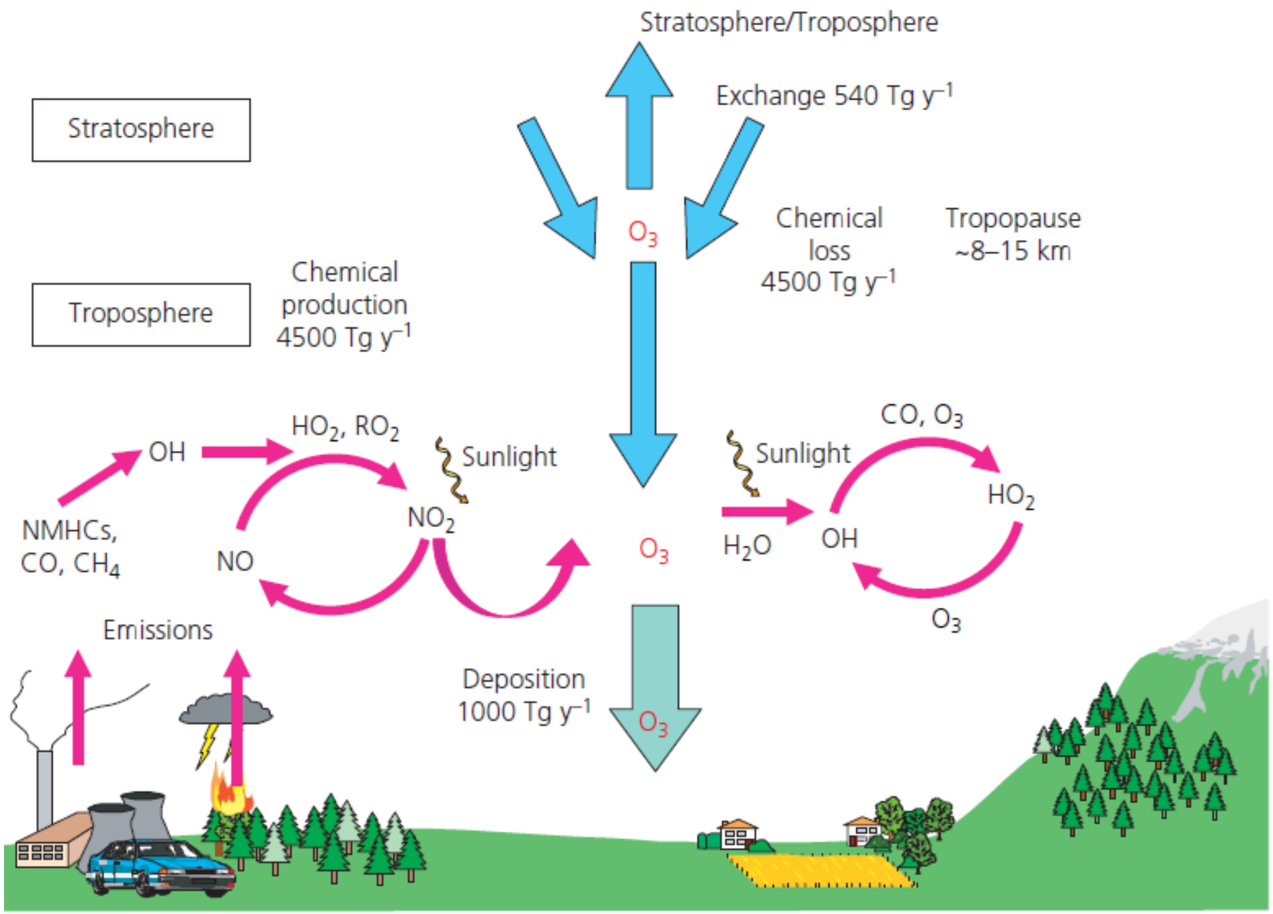
O_3 Sources & Sinks (yr 2000)



Stevenson et al., JGR, 111, D08301, 2006; Royal Society, 2008.

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The “Standard Model”

Consider three ‘resistances’ in series:

R_a: **A**erodynamic resistance

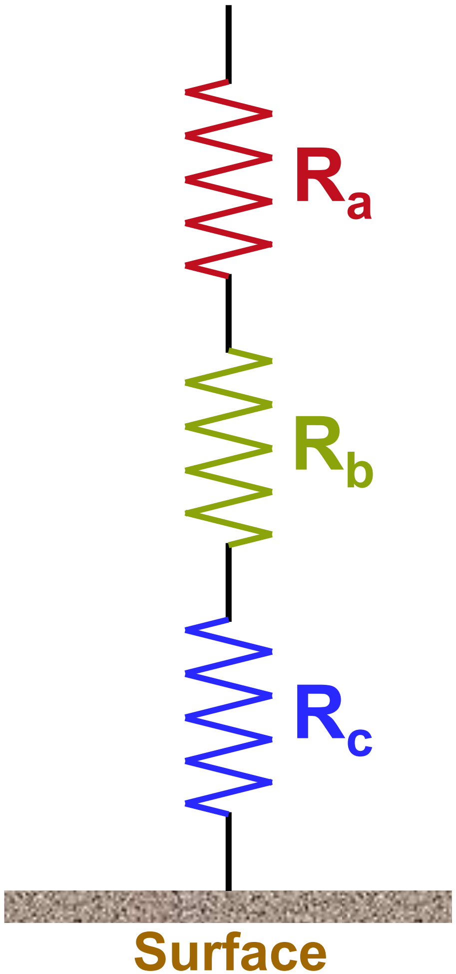
Depends on surface type

R_b: **B**oundary layer resistance
(‘quasi-laminar sub-layer resistance’)

Depends on species (diffusion coefficient)

R_c: **C**anopy (surface) resistance

Depends on surface type & species



Deposition velocity:

V_d = $1/(R_a + R_b + R_c)$
= Flux/Concentration (at reference height)
= $[kg\ m^{-2}\ s^{-1}]\ /\ [kg\ m^{-3}] = m\ s^{-1}$; $[R_i] = s\ m^{-1}$

Analogy: Flux ≡ Current
Concentration ≡ Voltage
Voltage = Current x Resistance →
1/R = I/V

c.f., M. L. Wesley, Atmos. Env., 25, 1293-1304, 1989.

O_3 Deposition In Models (HTAP)

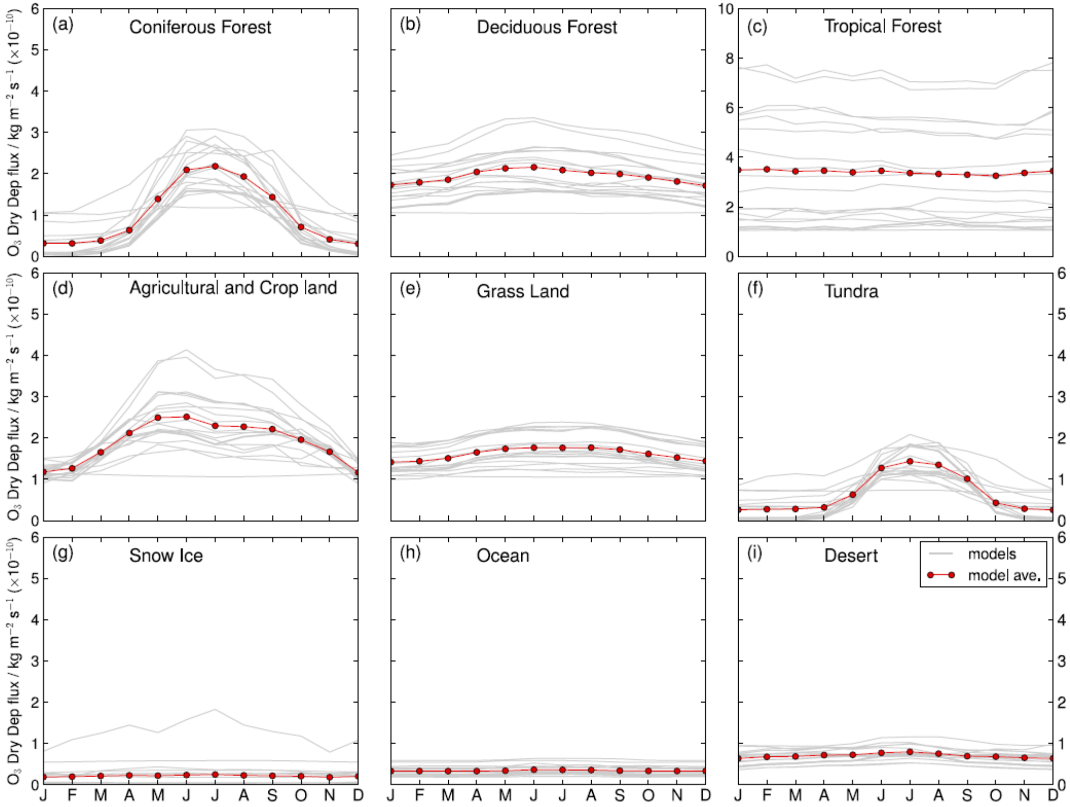
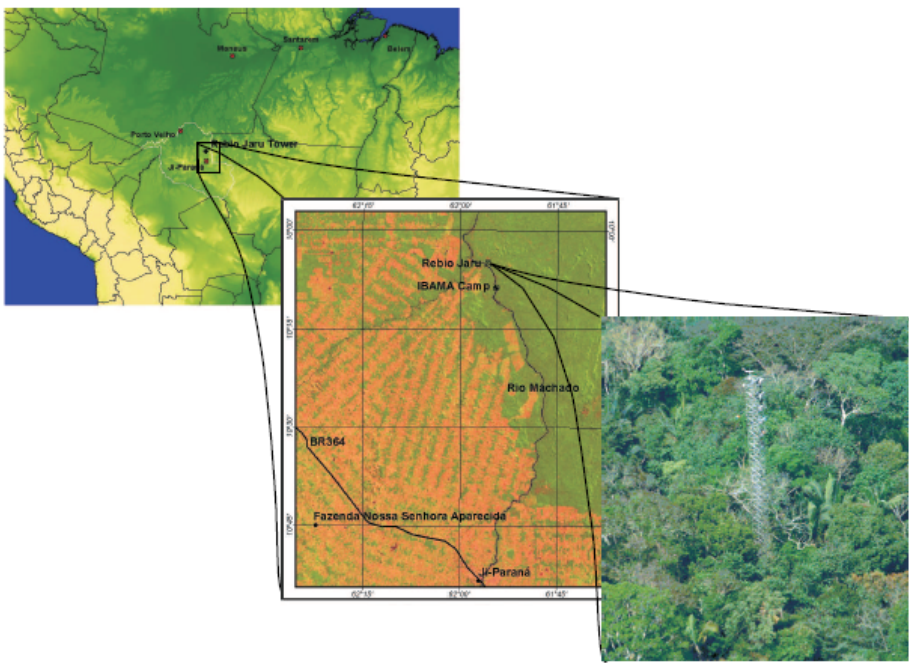


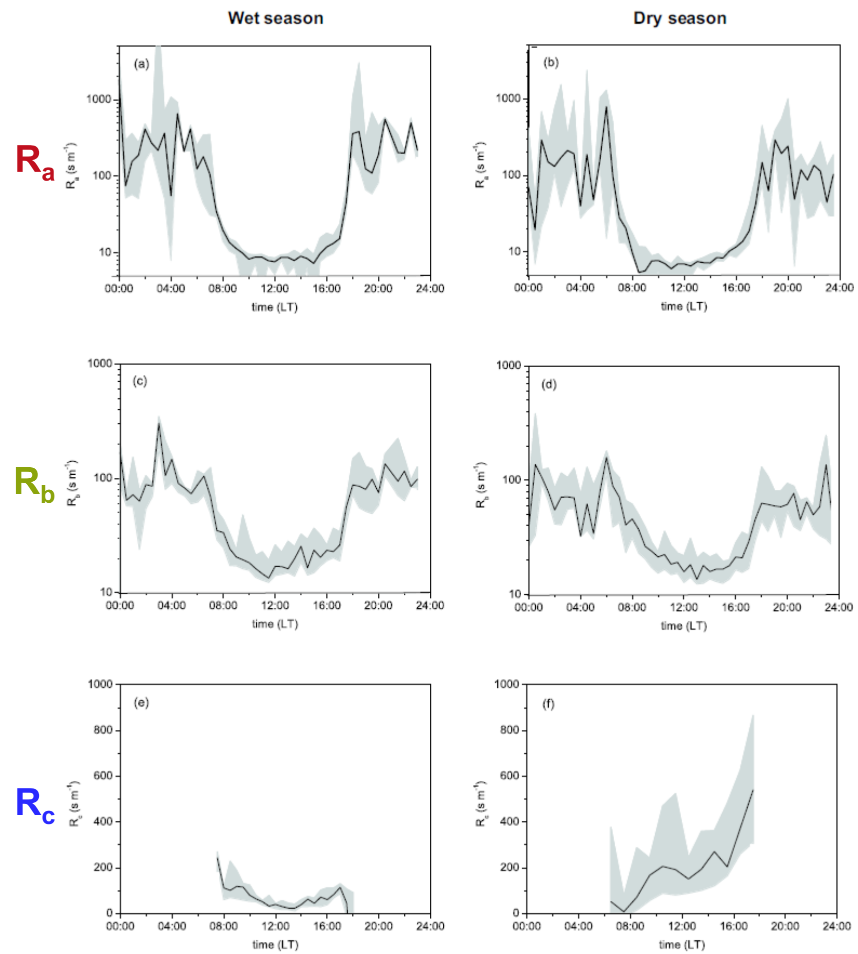
Figure 3. Normalised average monthly O_3 dry deposition at grid cells with 100 % land cover class coverage. Model fluxes are shown in grey and the ensemble average in red.

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

O_3 Deposition Measurements

At A Tropical Rain Forest in Southwest Amazonia

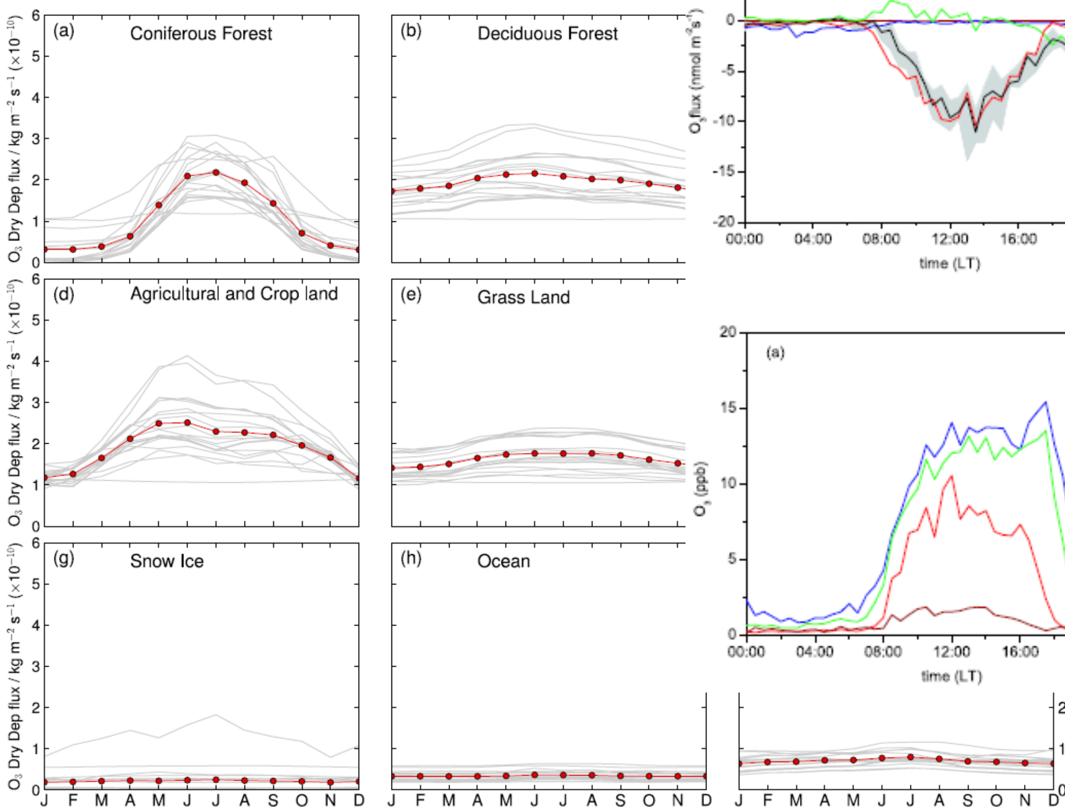


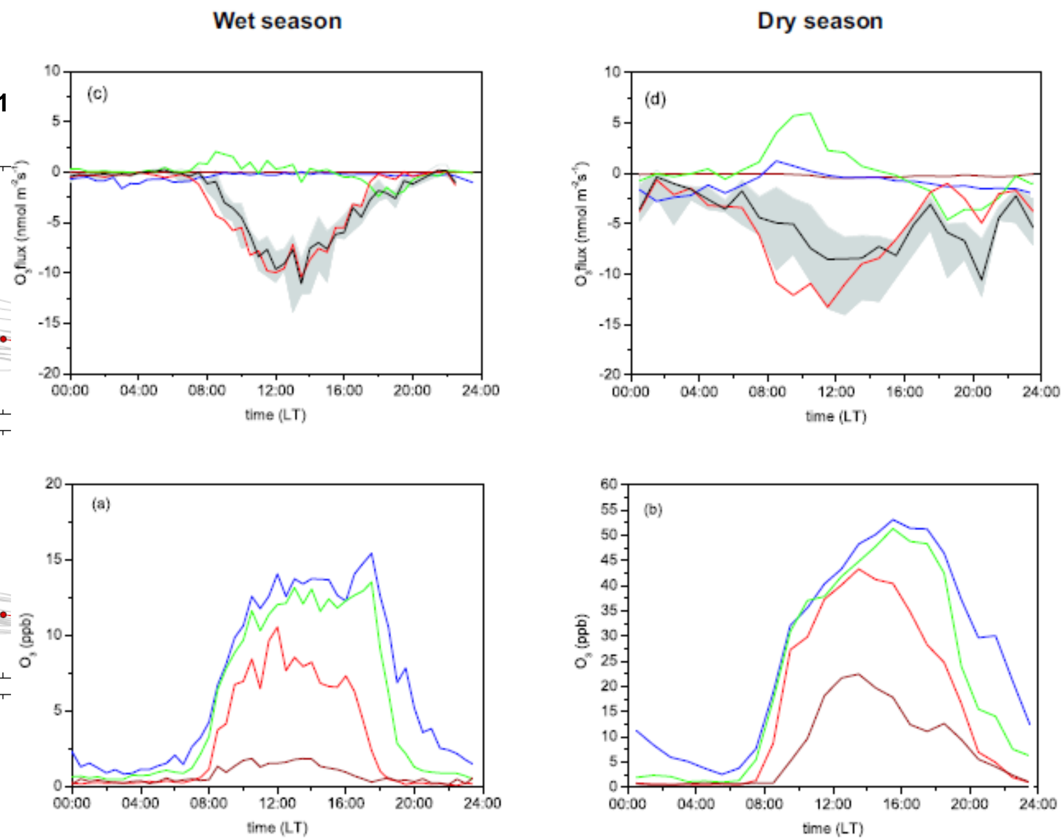


Rummel et al., ACP, 7, 5415-5435, 2007.

Model-to-Obs Comparison

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





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

Rummel et al., ACP, 7, 5415-5435, 2007.

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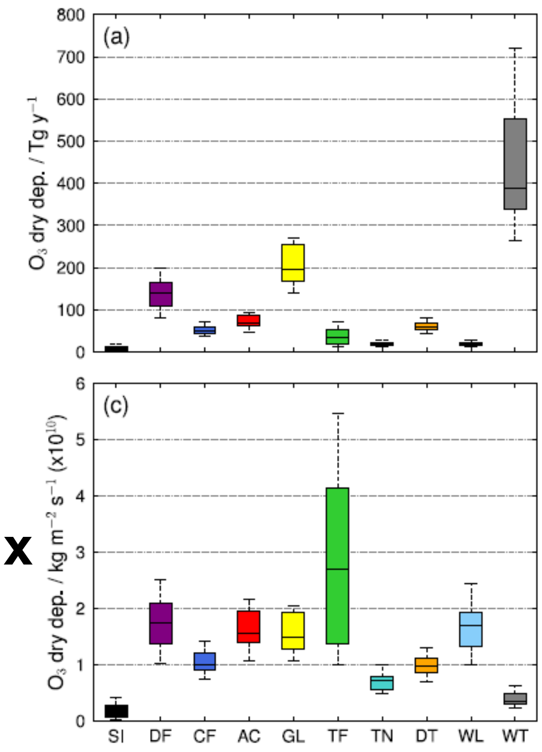
Different Land-Cover Classes

Total Annual Flux

Annual Average Flux



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 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., ACP, 15, 6419-6436, 2015.

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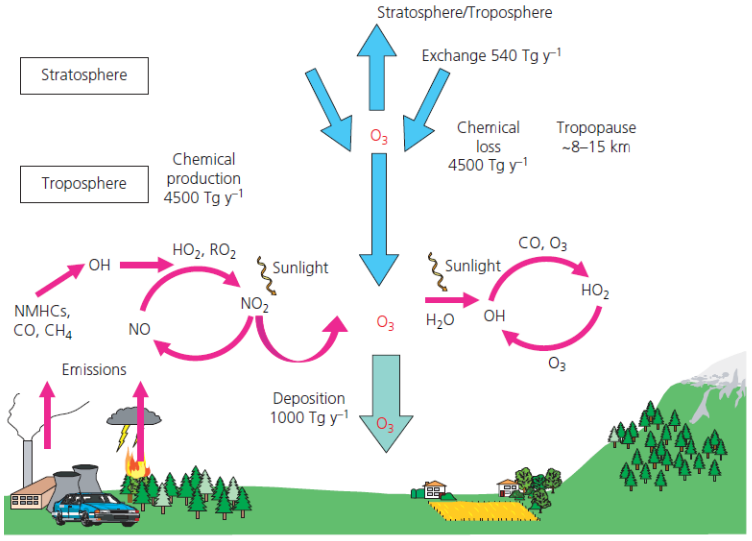
Importance Of Dry Deposition



- 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[1]
    - 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

Browning on potato leaves due to high ozone exposure.

(Photograph courtesy UDA-ARS Air Quality Program, North Carolina State University; photo by Gerald Holmes).

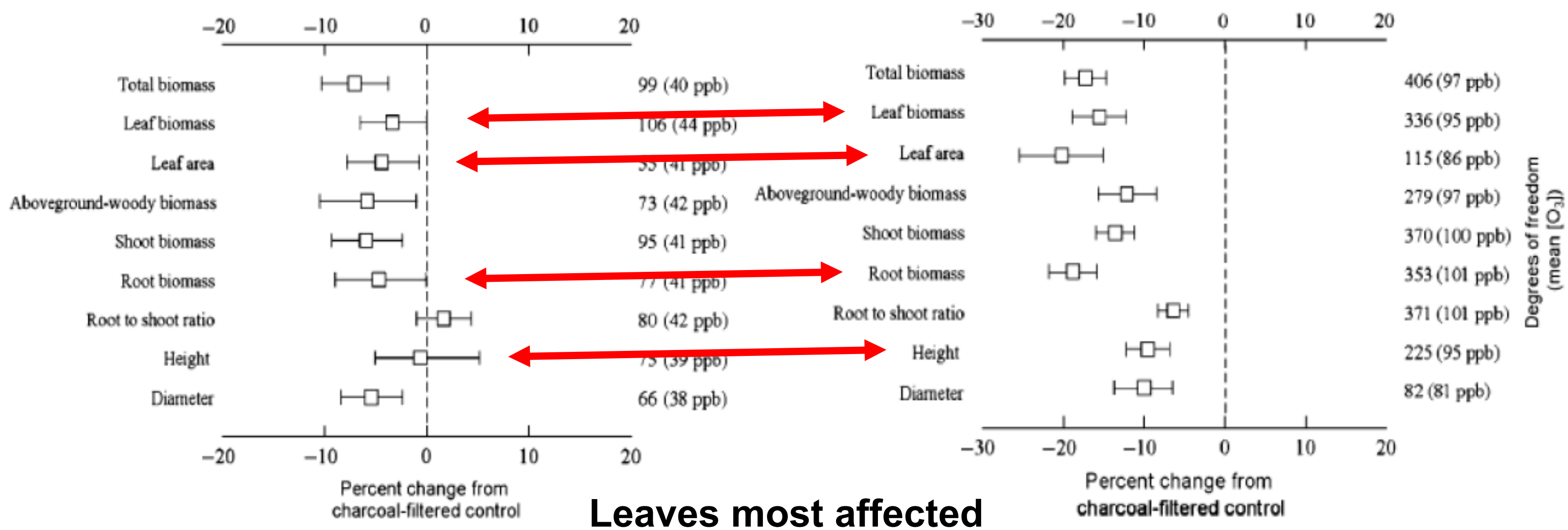
- Mechanism
  - leaf-internal cell damages
    - reddening, necrosis
  - reduced photosynthetic rates
  - accelerated leaf senescence
- Economic Impacts
  - reduced crop yields
  - global economic losses*
    - $14 - $26 billion annually
    - implications for food security

[*]R. Van Dingenen et al., Atmos. Env., pp. 604-618, 2009.

O_3-Impacts On Vegetation

Present-day and Future Ozone Impacts

O_3 impacts at ambient levels (~40 ppbv) | O_3 impacts at elevated levels (80-100 ppbv)



Leaves most affected

Wittig et al., GCB, 15, 396-424, 2009.

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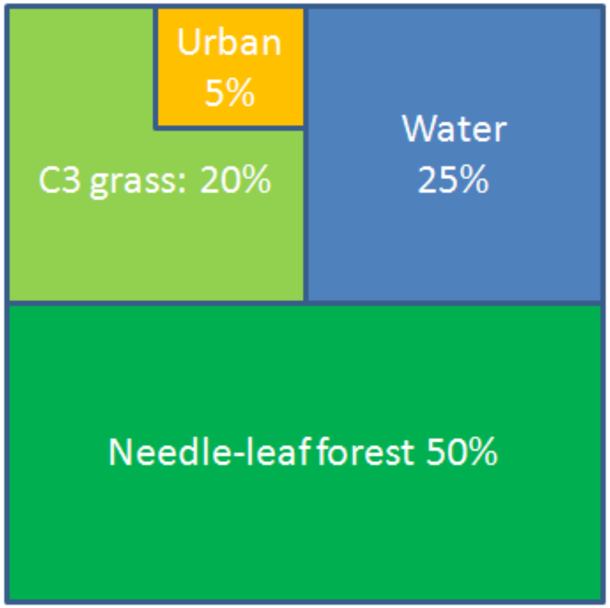
Its Representation In UKCA

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

Model Name	Formula
O3	O_3
NO	NO
NO2	NO_2
NO3	NO_3
N2O5	N_2O_5
HONO2	HNO_3
HONO	HONO
ISON	
H2SO4	H_2O_4
H2O2	H_2O_2
H2	H_2
CH3OOH	CH_3OOH
HACET	
ROOH	Other organic peroxides
PAN	} Peroxy Acetyl Nitrates
PPAN	} Peroxy Acetyl Nitrates
MPAN	} Peroxy Acetyl Nitrates
CO	CO
CH4	CH_4
NH3	NH_3
H2	H_2
SO2	SO_2
DMSO	
MSA	
OnitU	
SEC_ORG	Any other secondary organics
ORGNIT	Organic nitrogen

- 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

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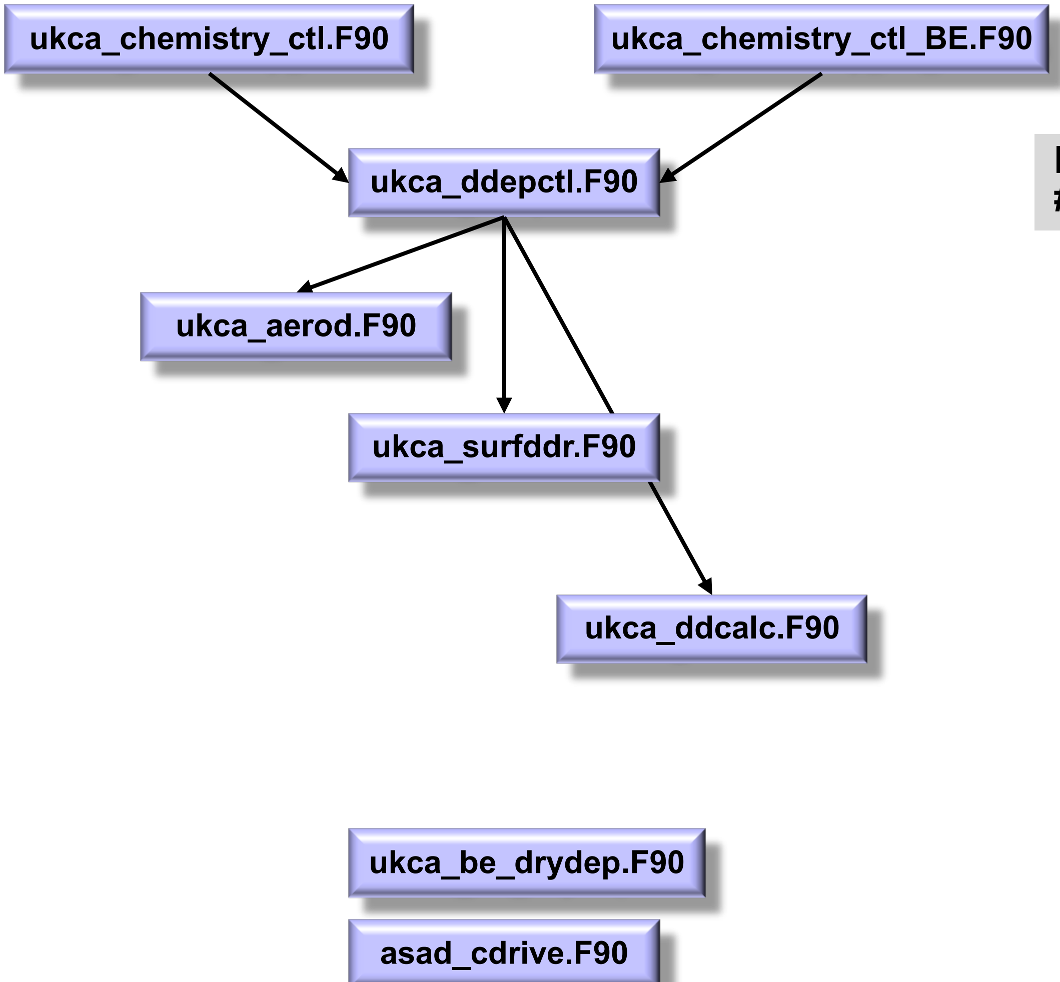
UKCA Calling Diagram



calling-level routines

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)

R_a and R_b Terms

Aerodynamic resistance:

$$R_a = \left(ln\left({}^{z}/_{z_0}\right) - \varphi\right) \Big/ {}_{ku^*}$$

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

Quasi-laminar sub-layer resistance:

$$R_b = \left({}^{Sc}/_{Pr}\right)^{2/3} \Big/ {}_{ku^*}$$

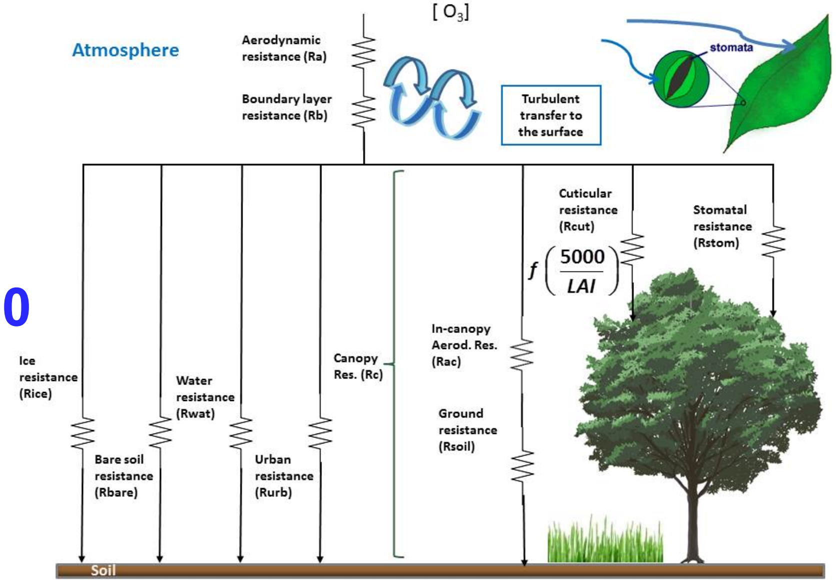
Sc: Schmidt Number (diffusion vs. viscosity)

Pr: Prandtl Number (0.72 for lower atmosphere)

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

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**



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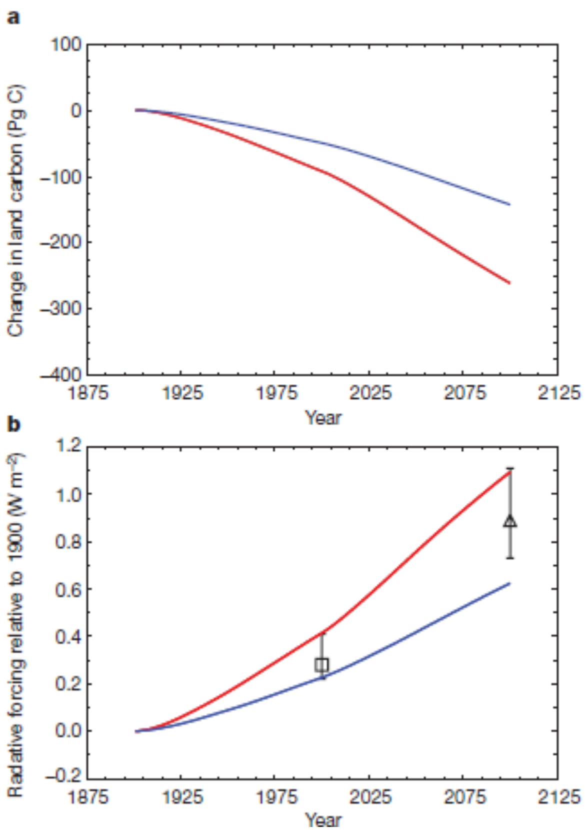
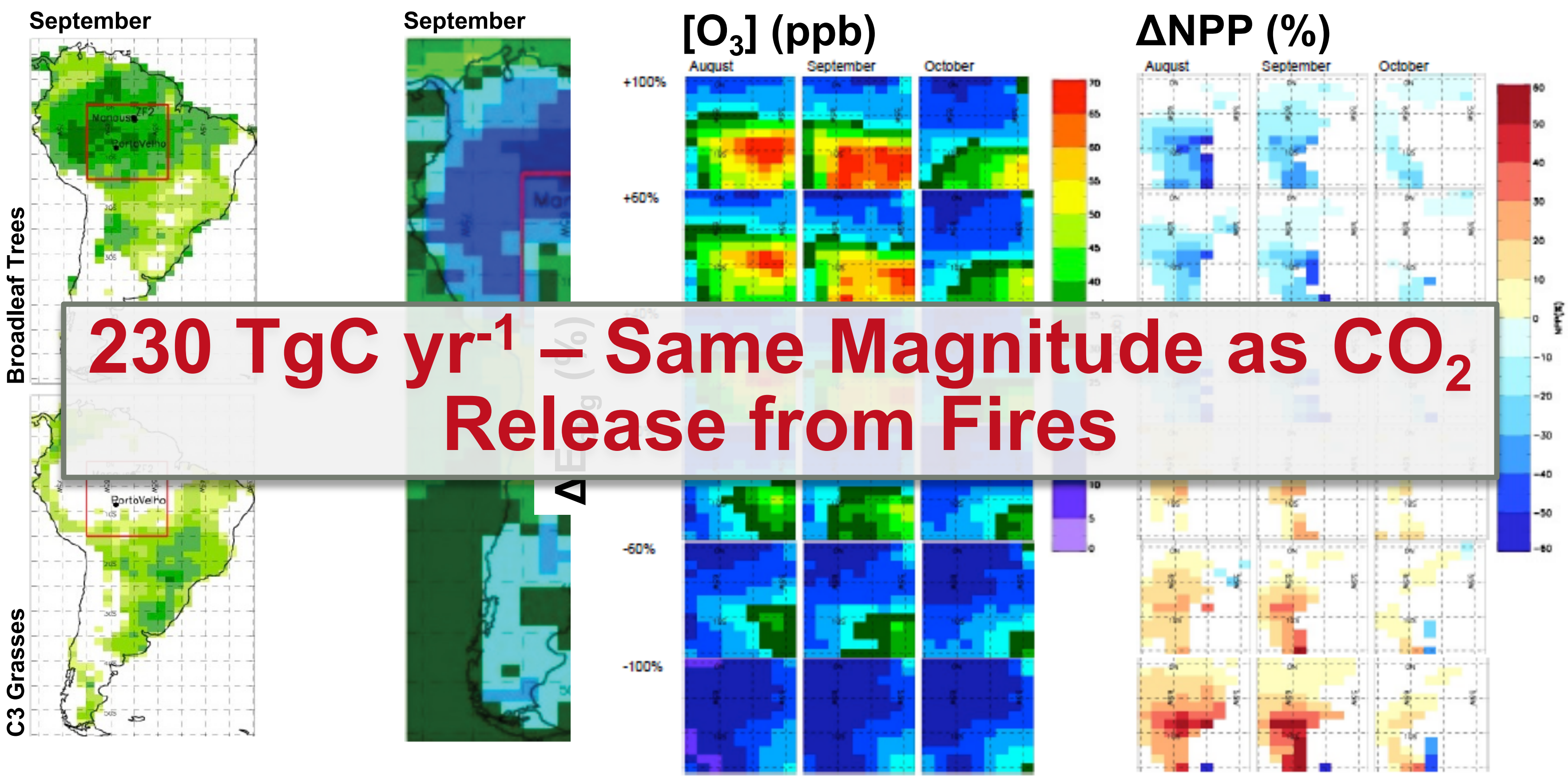
Application in Research



- O_3-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 O_3 RF: 0.89 W m^{-2}

S. Sitch et al., Nature, August 2007; doi:10.1038/nature06059.

O_3-Dry Deposition in Ecosystems



230 TgC yr[-1] – Same Magnitude as CO_2 Release from Fires

F. Pacifico et al., ACP, 15, pp. 2791-2804, 2015.

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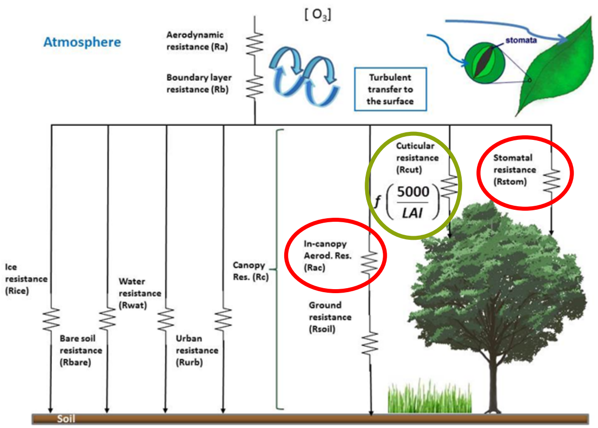
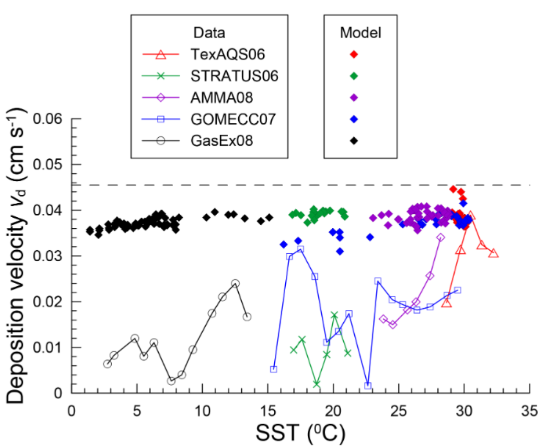
Selected Recent Work



- **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

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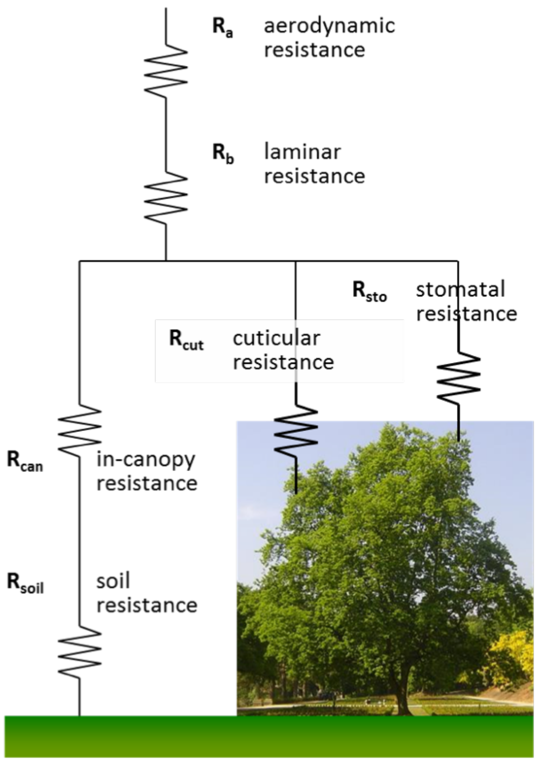
Future Developments

- 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...