Dry Deposition in UKCA

David Stevenson & Federico Centoni
(dstevens@staffmail.ed.ac.uk)

The University of Edinburgh

UKCA Training Course, Cambridge, 5-9 January 2015

http://macaqueedinburgh.wordpress.com/

MACAQUE: Modelling and measuring Atmospheric Composition and Air QUality at Edinburgh

Acknowledgements

- Federico Centoni (UoE)
  - Much of this is his PhD work
- David Fowler, Eiko Nemitz (CEH Edinburgh)
- Catherine Hardacre, Oliver Wild (Lancaster Uni), Lisa Emberson (SEI-York)
- Gerd Folberth (Met Office)
- Luke Abraham
- Mike Sanderson (Met Office)

Outline

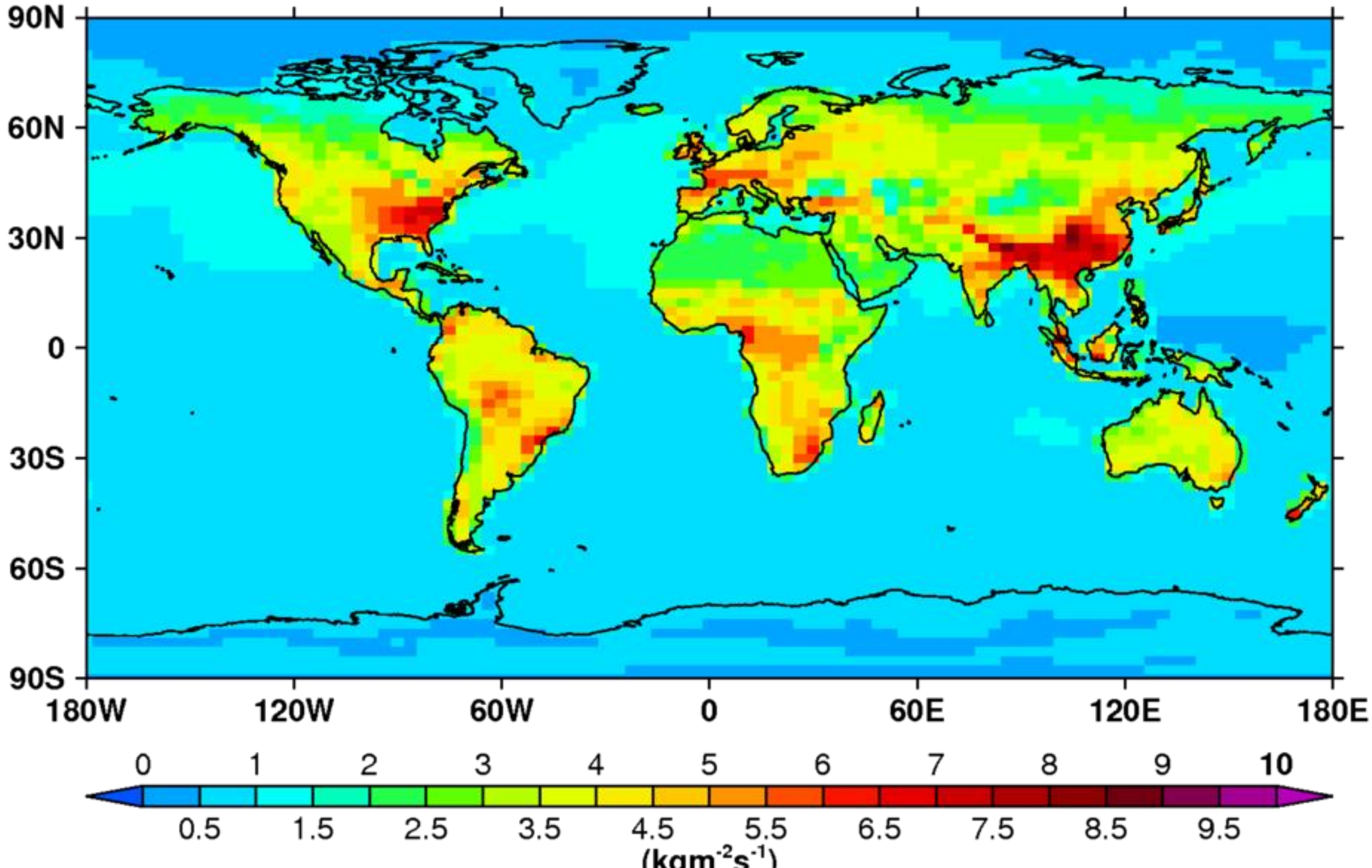
- What is dry deposition?
- Why is it interesting/important?
- How is it represented in UKCA?
- Model improvements underway/planned
- Research questions related to dry deposition

What is dry deposition?

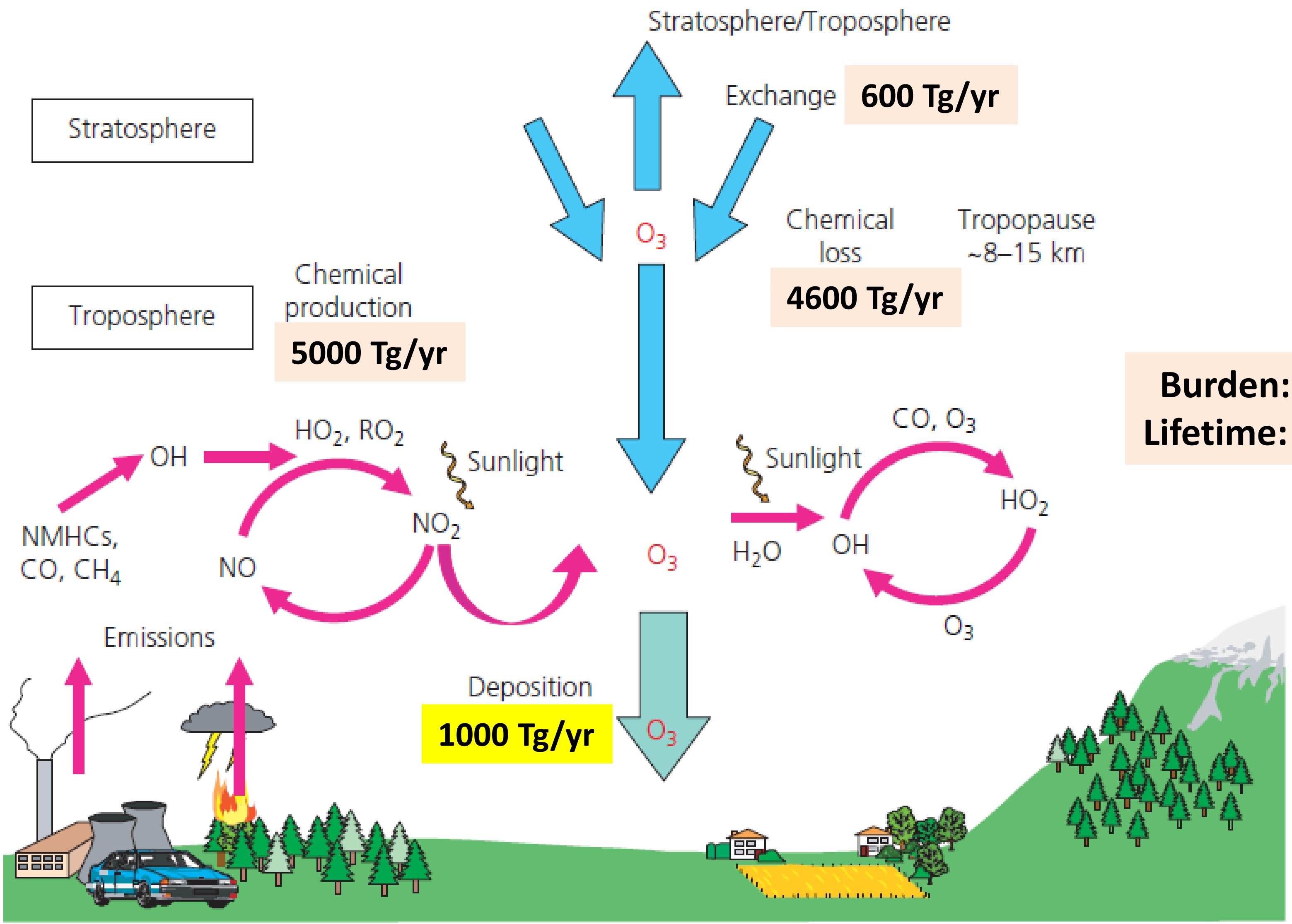
- Removal of gases and aerosols by turbulent transfer and uptake at the Earth's surface
- Process operates on air in boundary layer
- Important sink for many species (O_3, H_2O_2, NO_2, PAN, HNO_3, NH_3, aerosols, CH_4, H_2, CO, …)
- Controlled by: BL characteristics – depth, turbulence, diffusion, surface 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)



Burden: 340 Tg
Lifetime: 22 days

Stevenson et al 2006; Royal Society, 2008

O_3 dry deposition 'velocities' in the HTAP models

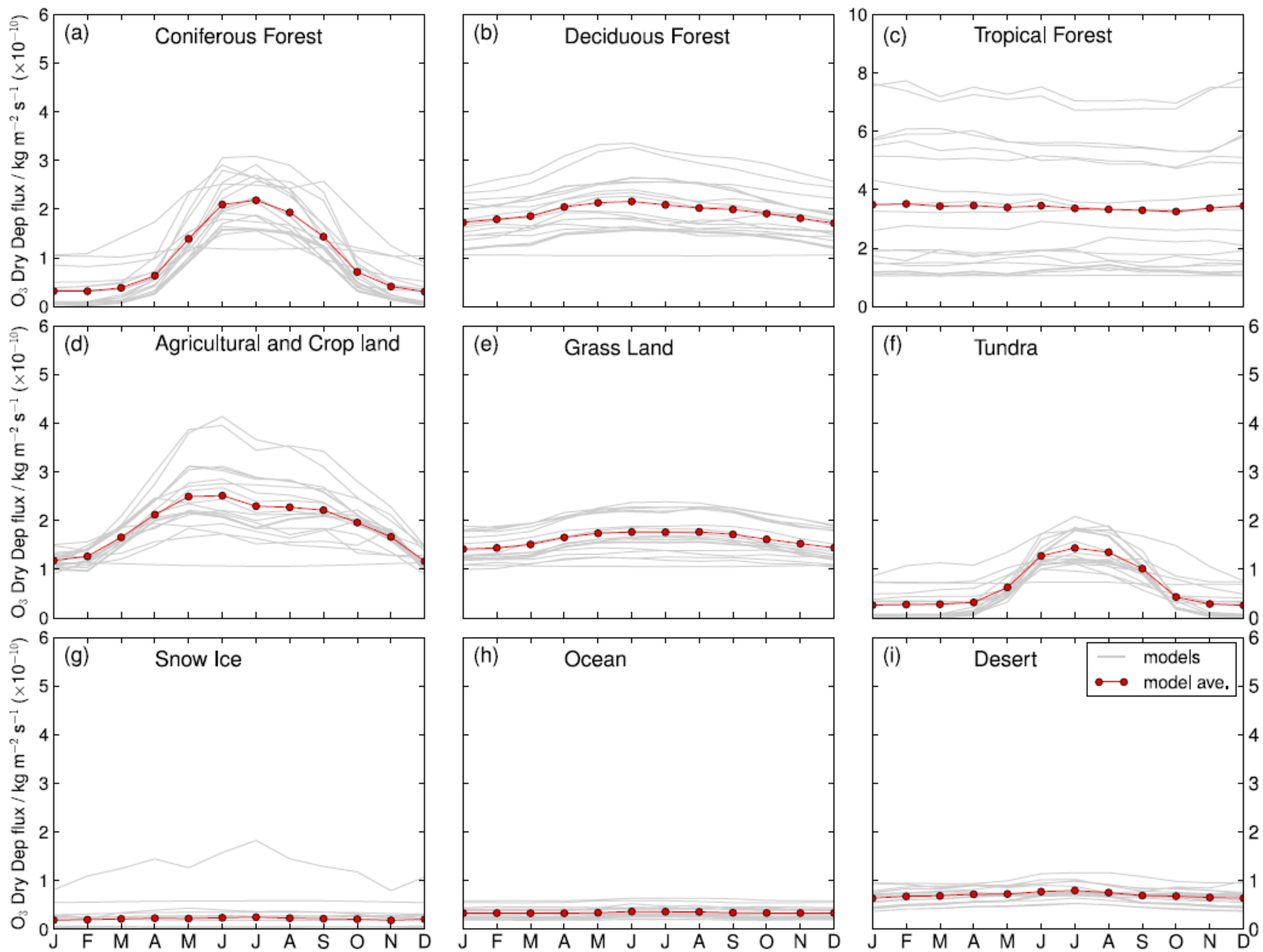


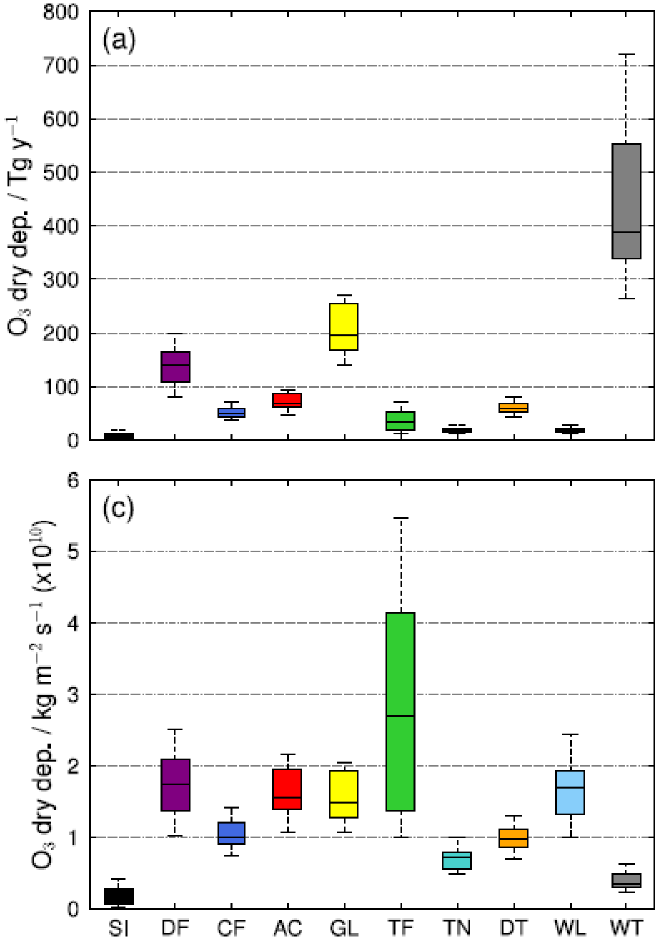
Figure 3. Normalised average monthly O_3 dry deposition at grid cells with 100 % land cover class coverage. Model fluxes are shown in grey and the ensemble average in red.

Hardacre et al. (2014)

O_3 deposition to different land-cover types

Absolute fluxes

Normalised fluxes



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: **A**erodynamic resistance

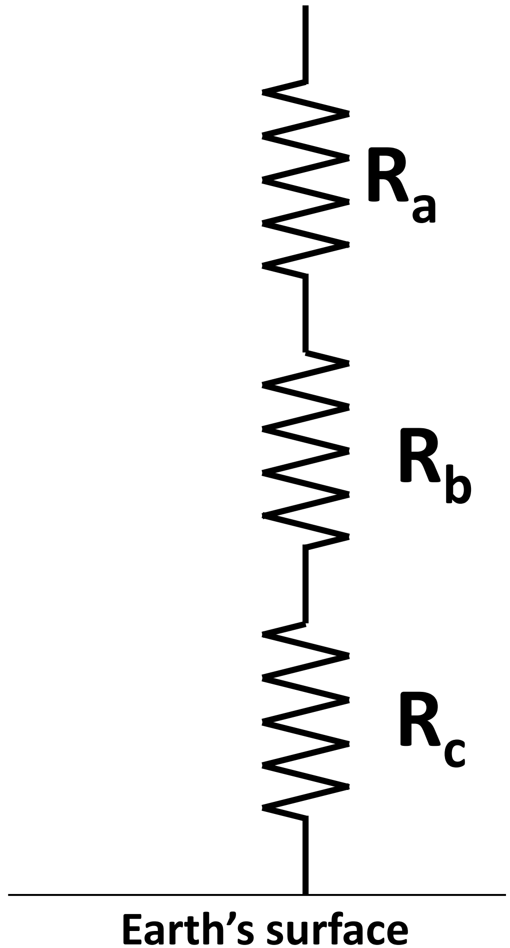
Depends on surface type

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:

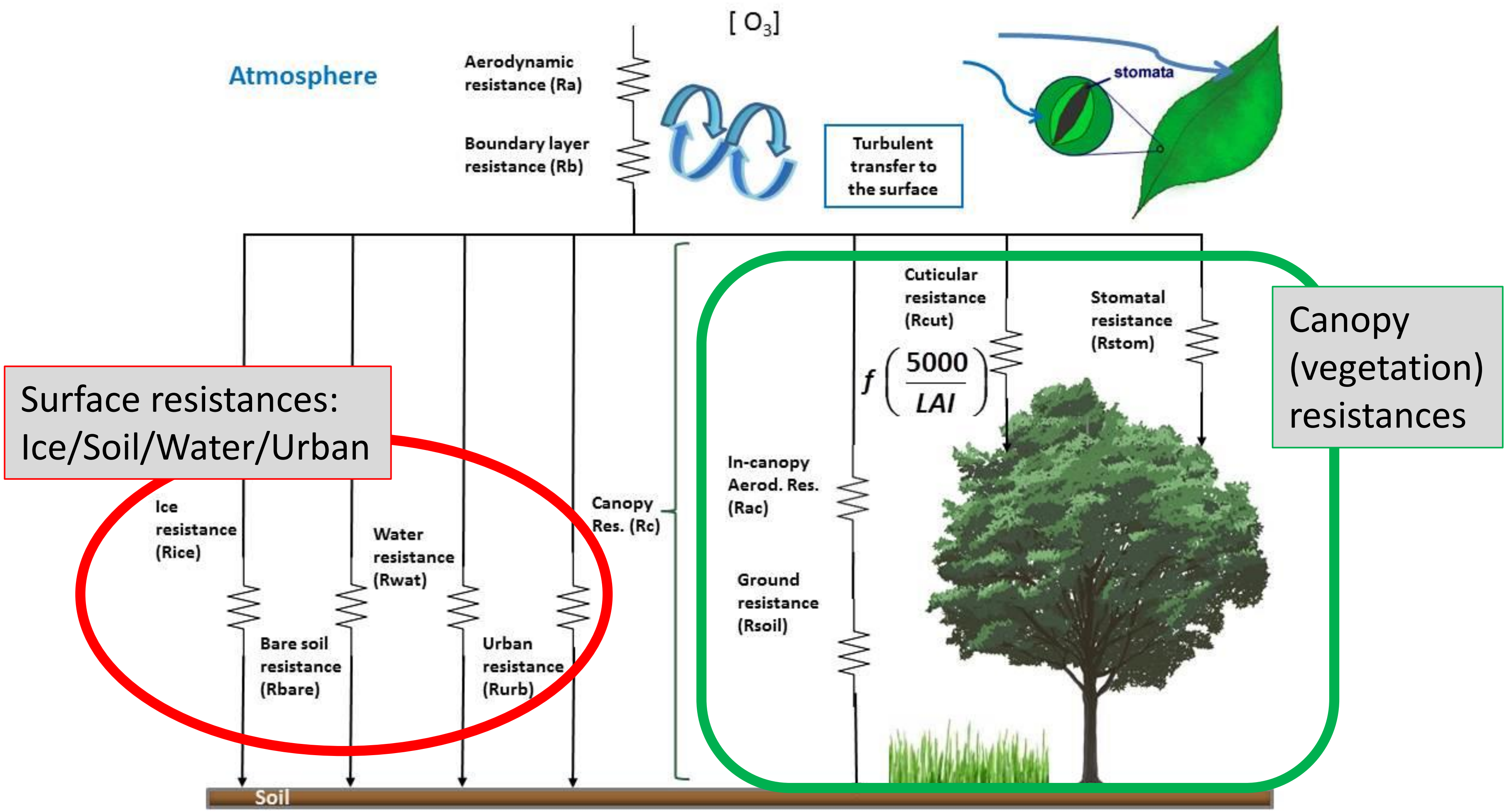
$V_d = 1/(R_a + R_b + R_c)$

= Flux/Concentration (at ref ht)

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

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

Expanded surface/canopy resistance terms

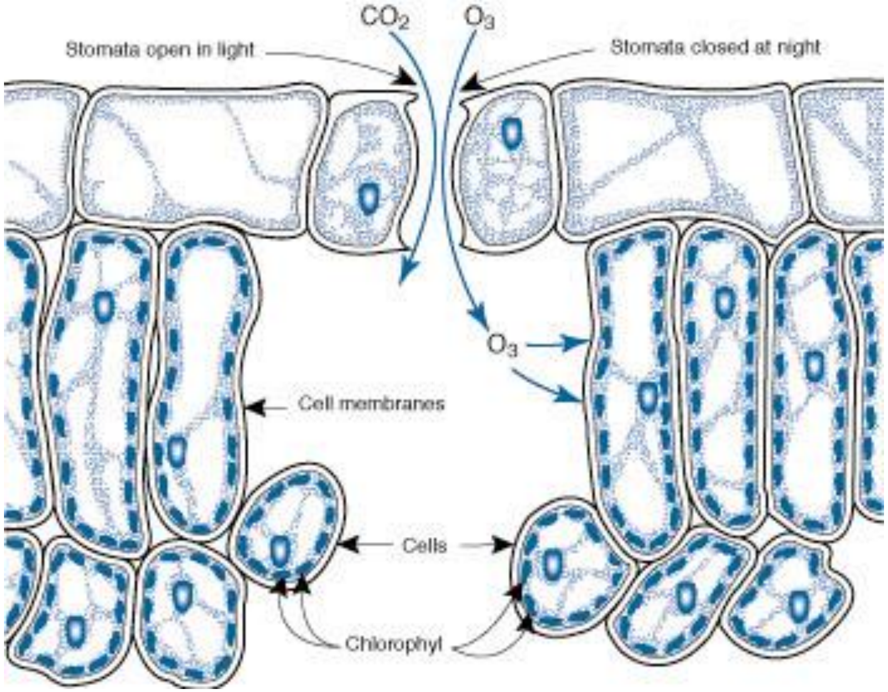


Federico Centoni, after Wesely (1989)

Aside:
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

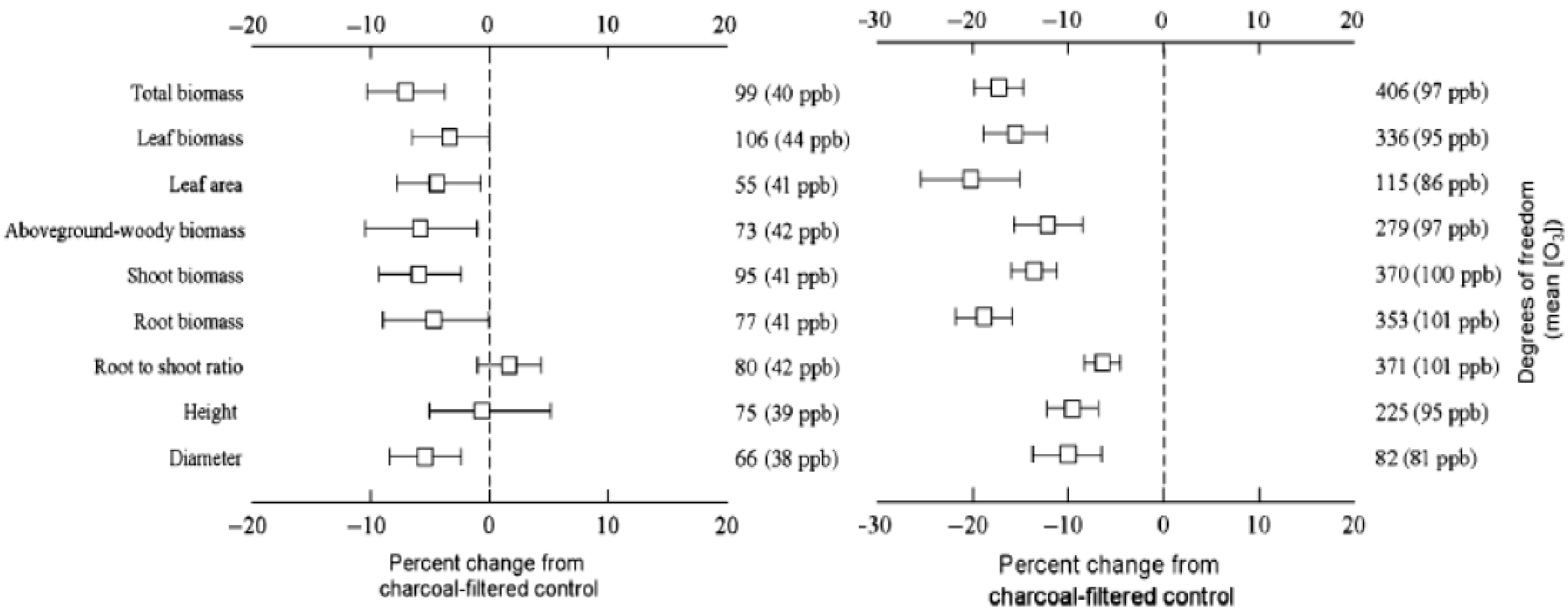
‘FACE’ experiments (Free Air CO_2 enrichment)

Also ozone – see http://aspenface.mtu.edu

Global Change Biology (2009) 15, 396–424, doi: 10.1111/j.1365-2486.2008.01774.x

Quantifying the impact of current and future tropospheric ozone on tree biomass, growth, physiology and biochemistry: a quantitative meta-analysis

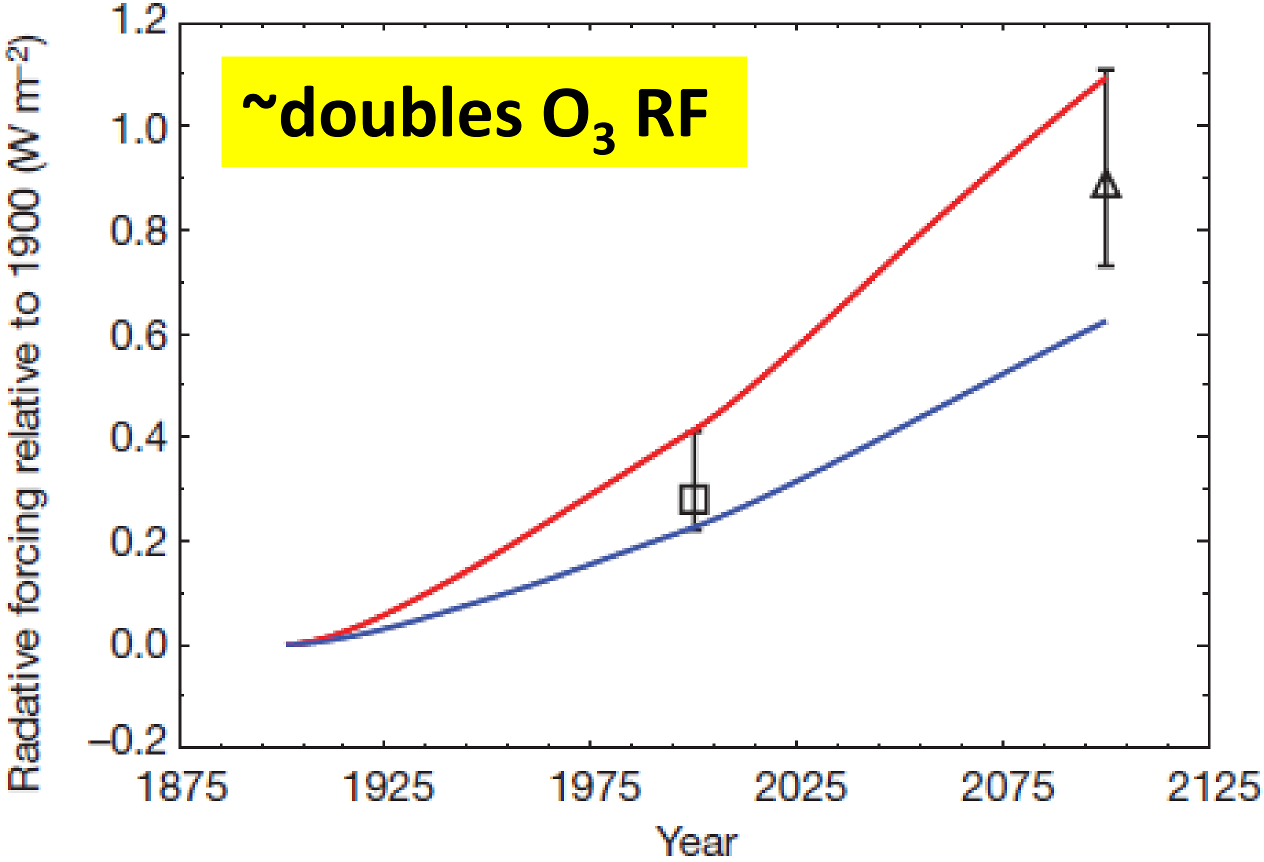
VICTORIA E. WITTIG*, ELIZABETH A. AINSWORTH*†, SHAWNA L. NAIDU‡, DAVID F. KARNOSKY§ and STEPHEN P. LONG*



Ozone impacts at ambient levels (~40 ppb)

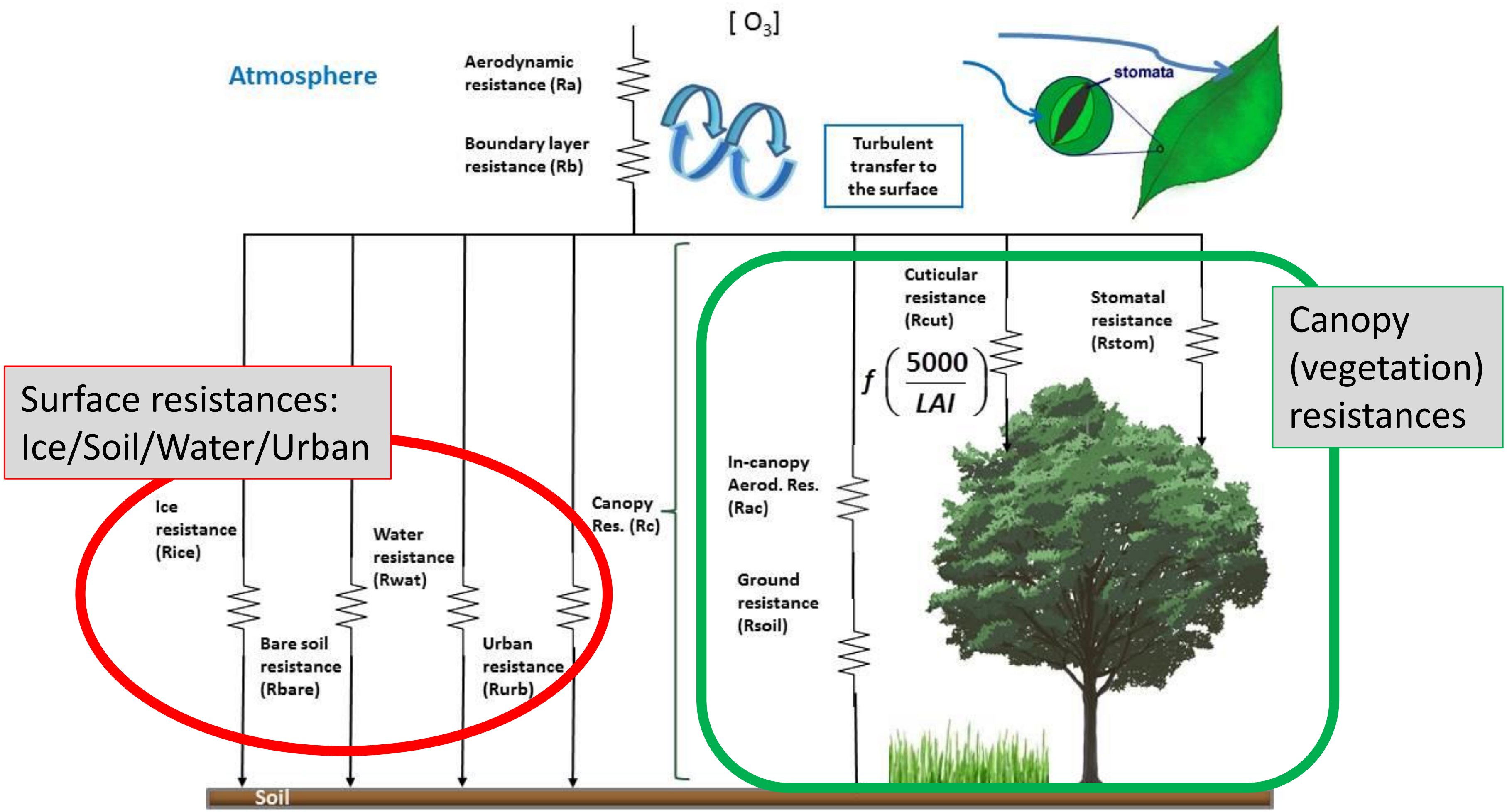
Ozone impacts at elevated levels (~80-100 ppb)

Indirect O_3 radiative forcing, via reduced C-sequestration



Sitch et al. (2007)

Expanded surface/canopy resistance terms



Federico Centoni, after Wesely (1989)

Aerodynamic resistance: R_a

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

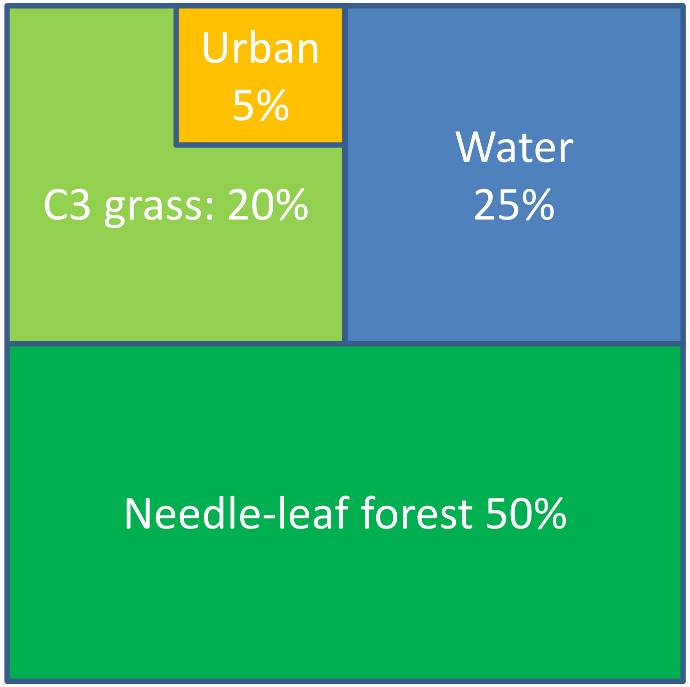
$$R_a = (\ln(z/z_0) - \varphi)/ku_*$$

- 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.

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

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)

ukca_ddcalc

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_be_drydep

Backward-Euler specific version of zdryrt

asad_cdrive

Loss rate from dry deposition integrated into all production/loss processes for each species

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_2SO_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
SO2	SO_2
DMSO	
MSA	
OnitU	
SEC_ORG	Any other secondary organics
ORGNIT	Organic nitrogen

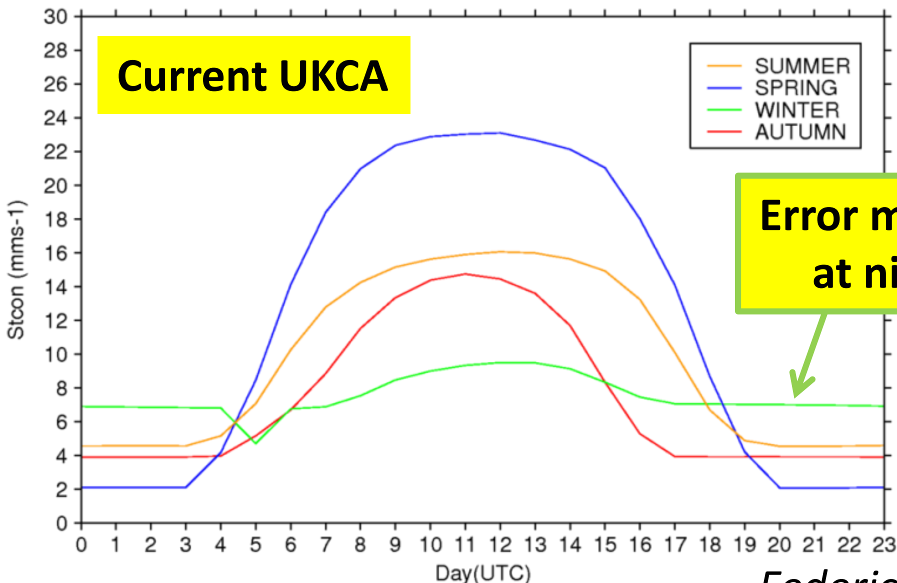
Examples to follow focus on ozone, but NB many species dry deposited

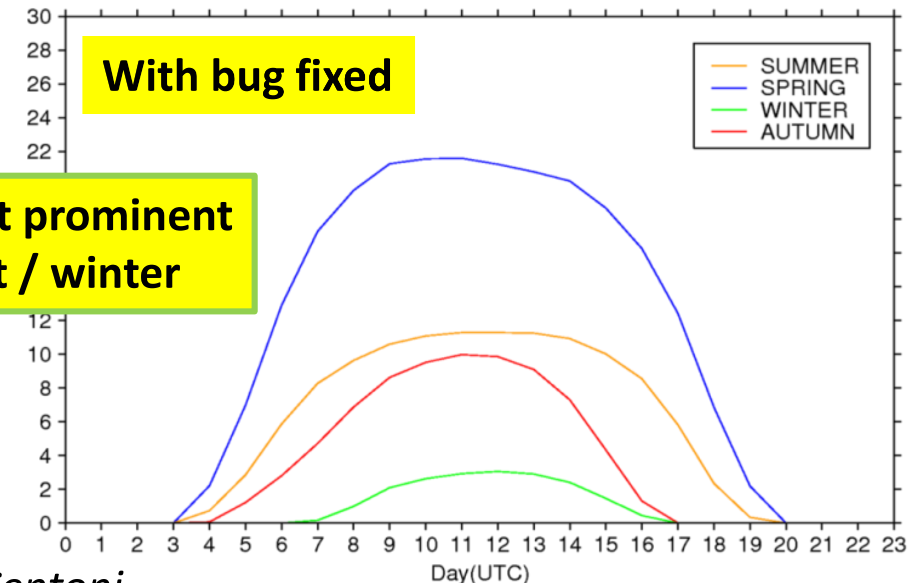
Abraham et al. (2012)

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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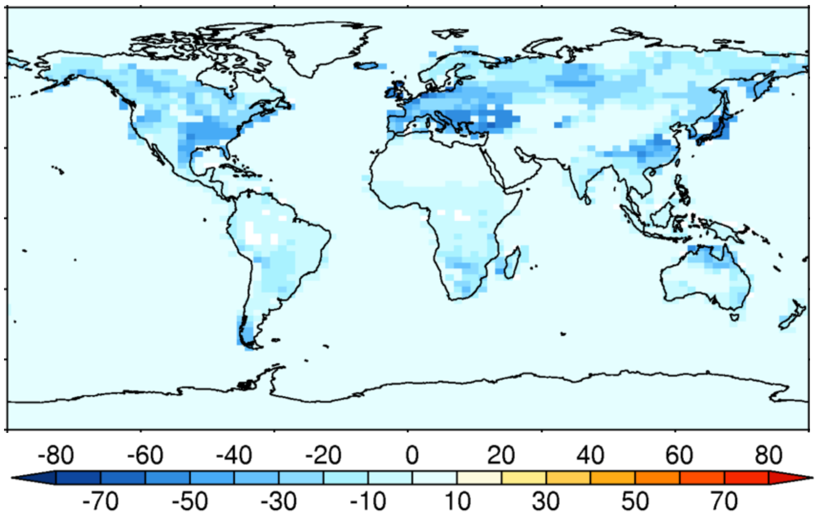
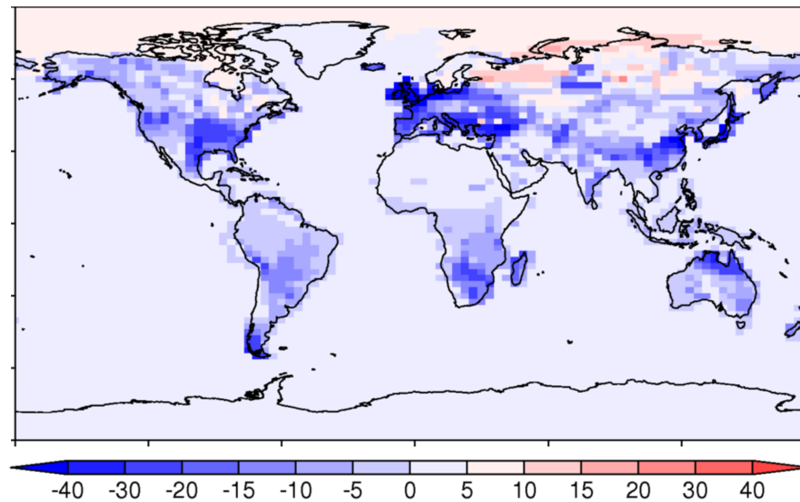
Global impact of the stomatal bug fix

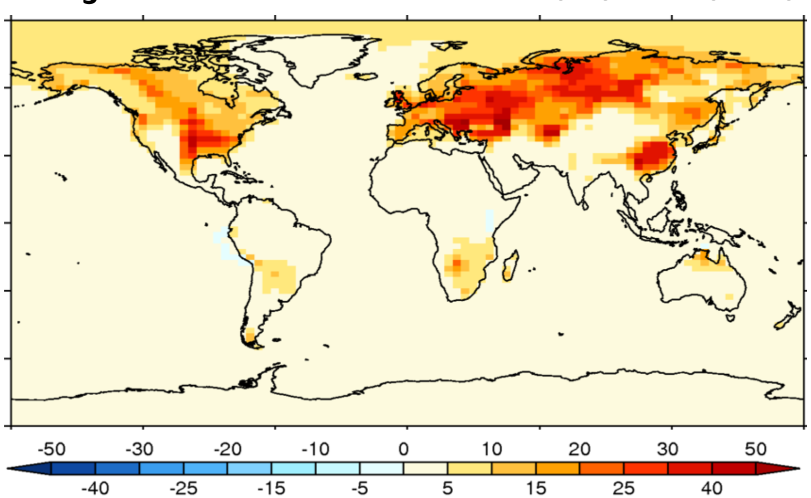
ΔO_3 deposition velocity (%) **(Jan)**



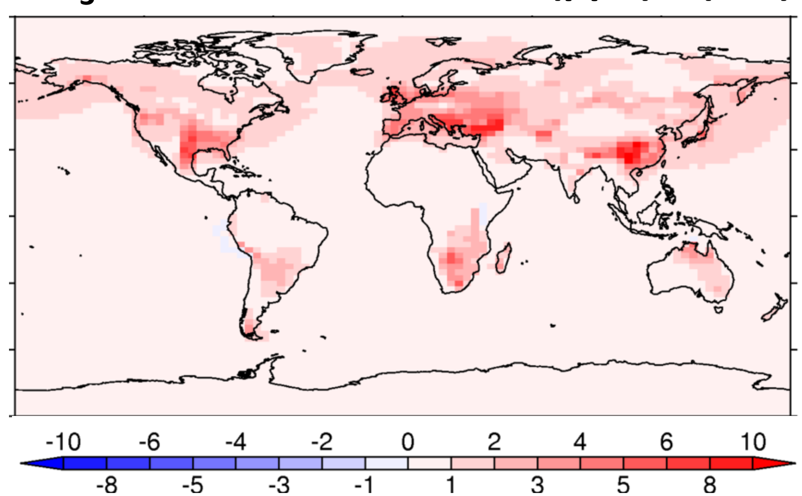
ΔO_3 deposition flux (%) **(Jan)**



ΔO_3 surface concentration (%) **(Jan)**



ΔO_3 surface concentration (ppb) **(Jan)**



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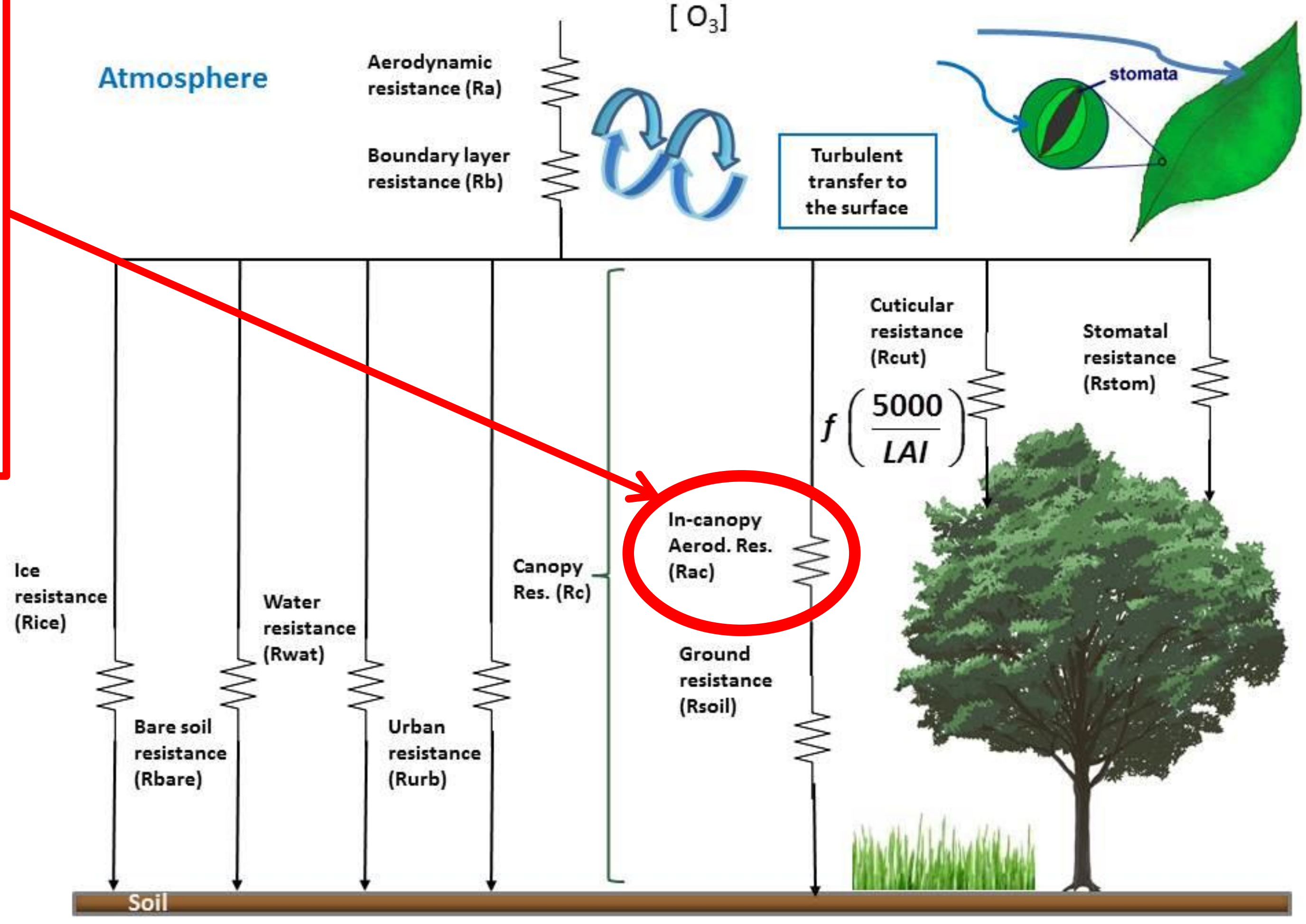
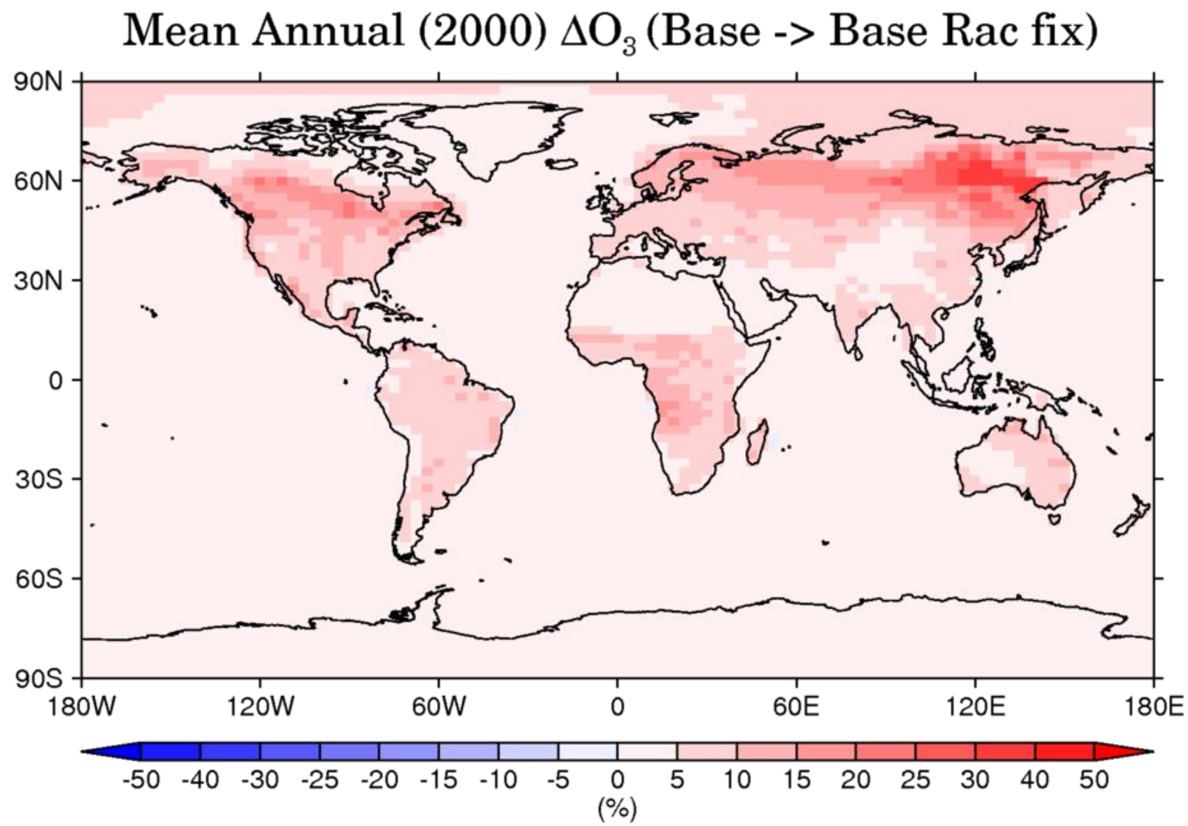
Bug fix 2: In-canopy resistance

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



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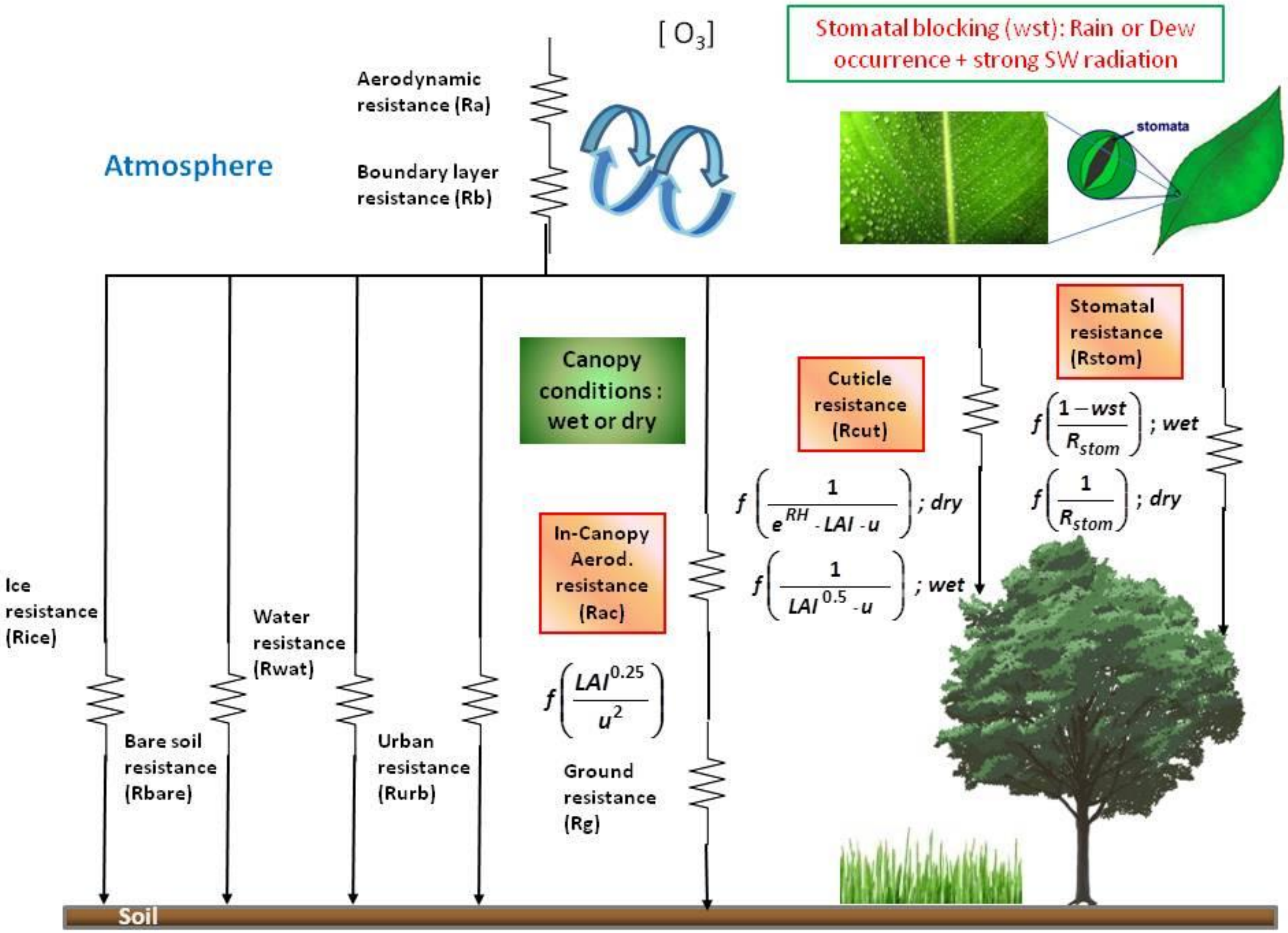
Adding the resistance term reduces deposition, particularly over forests, so O_3 concentrations increase.
[Caveat: I am unsure if R_{ac} terms still need to be added for all species:
I think here only the O_3 R_{ac} terms have been added; this is probably important.]

Further code developments: Zhang et al. (2003)



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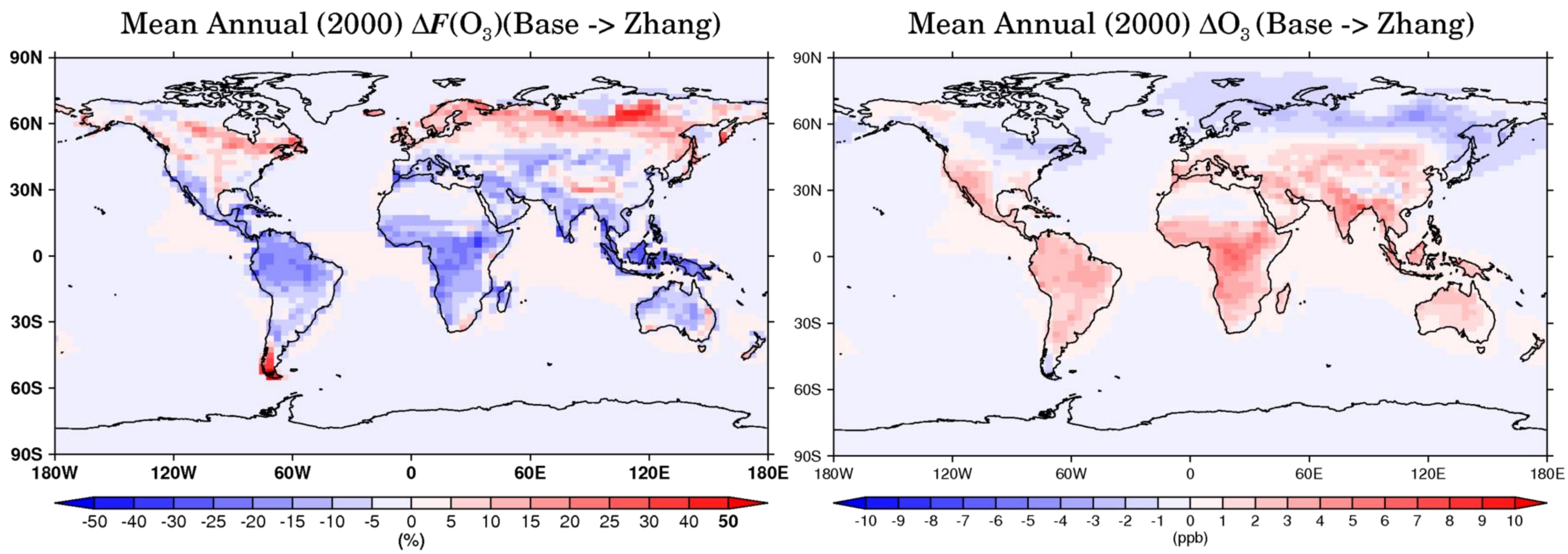
Impacts of Zhang et al scheme on O_3 deposition flux & surface O_3 concentration



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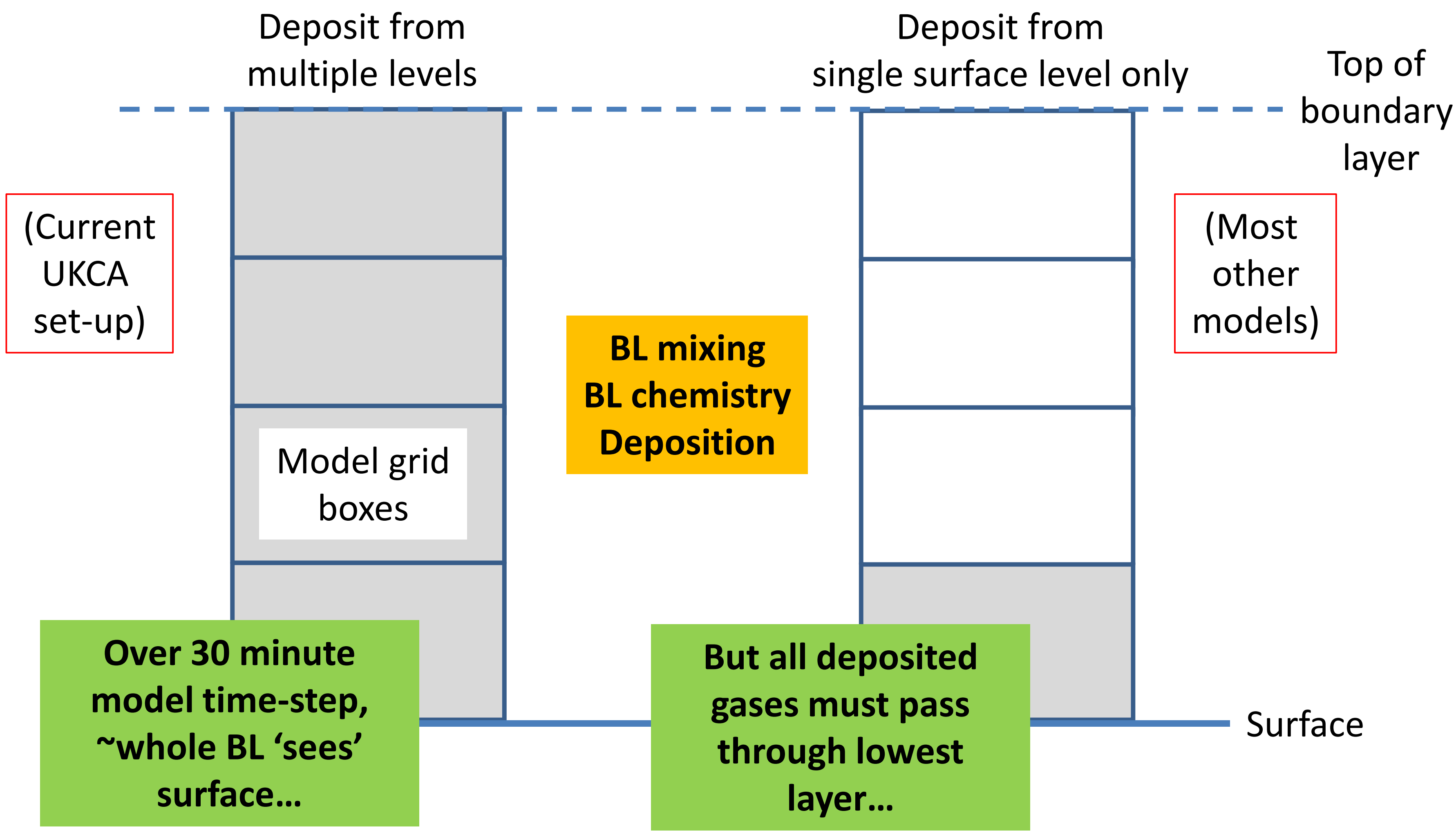
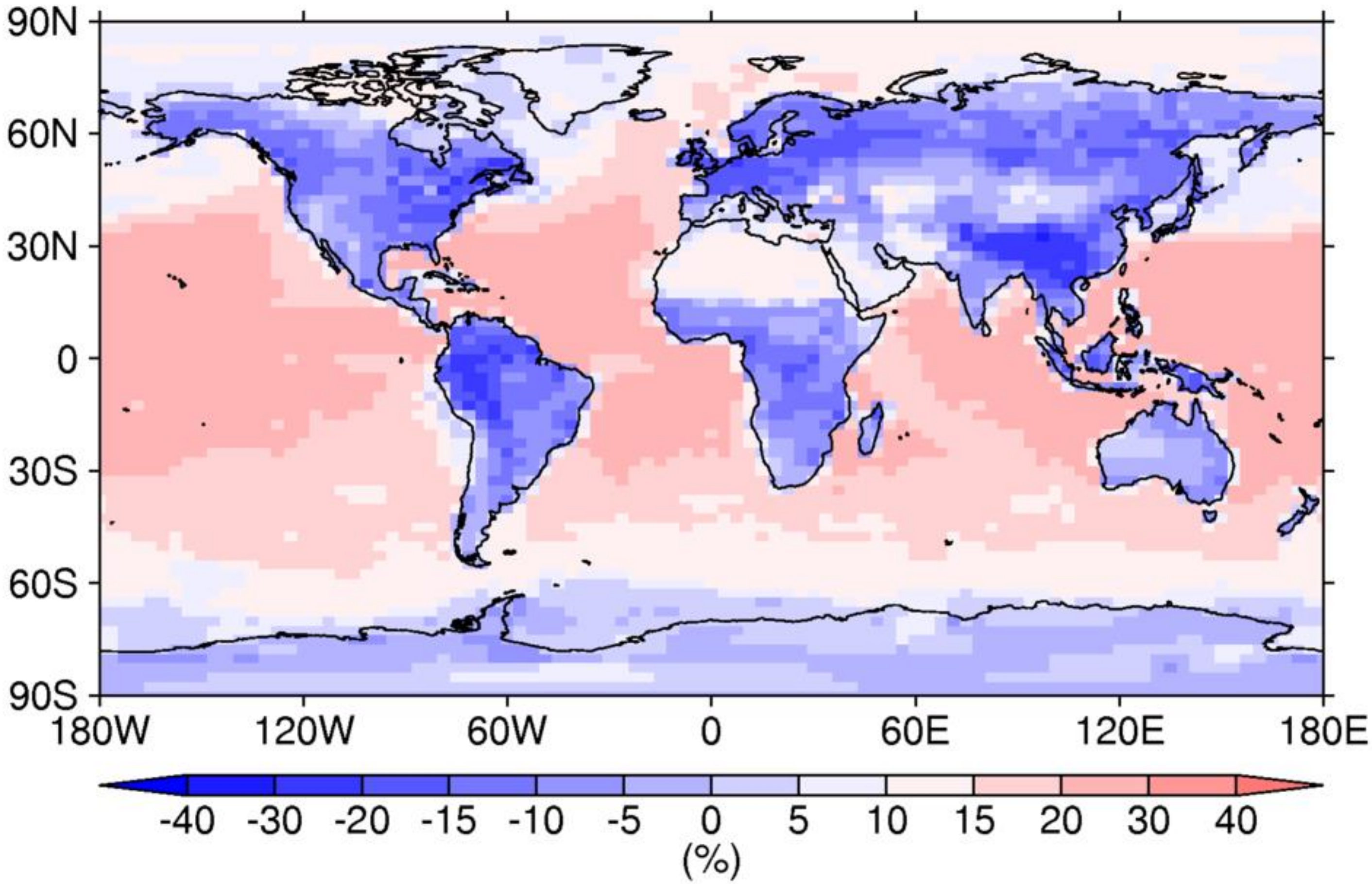
Currently evaluating whether the Zhang scheme improves comparisons with observations

Modelling dry deposition:
How do we formulate 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)



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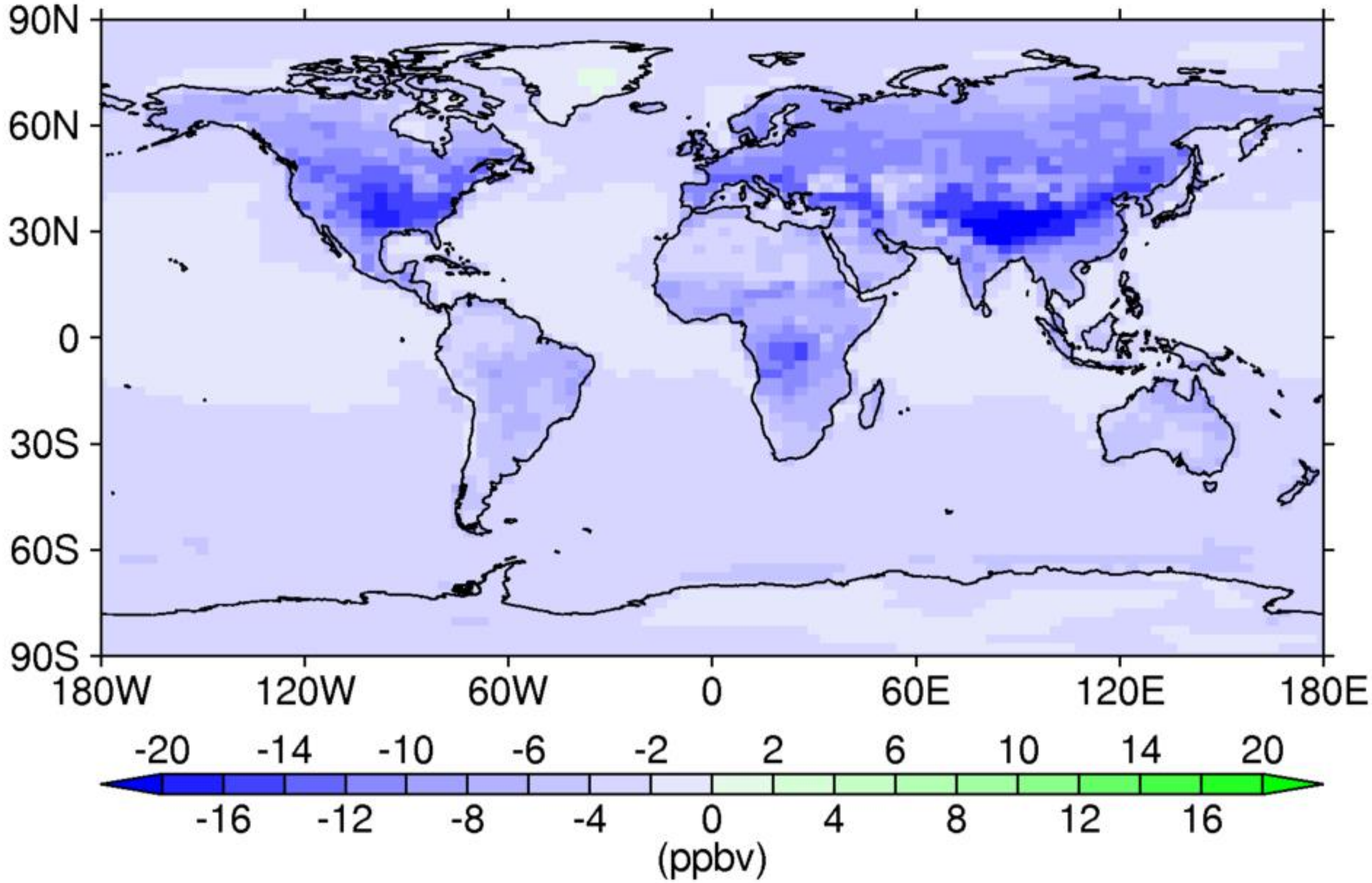
Global total O_3 dep flux remains at ~1100 Tg/yr

Big differences in simulated surface O_3 …

Change in 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.)