Dry Deposition in UKCA

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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

Revising dry deposition in the UKCA model and a different non-stomatal deposition approach, in prep GMD

Evaluation of ozone dry deposition velocity within the UKCA model, in prep ACP

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

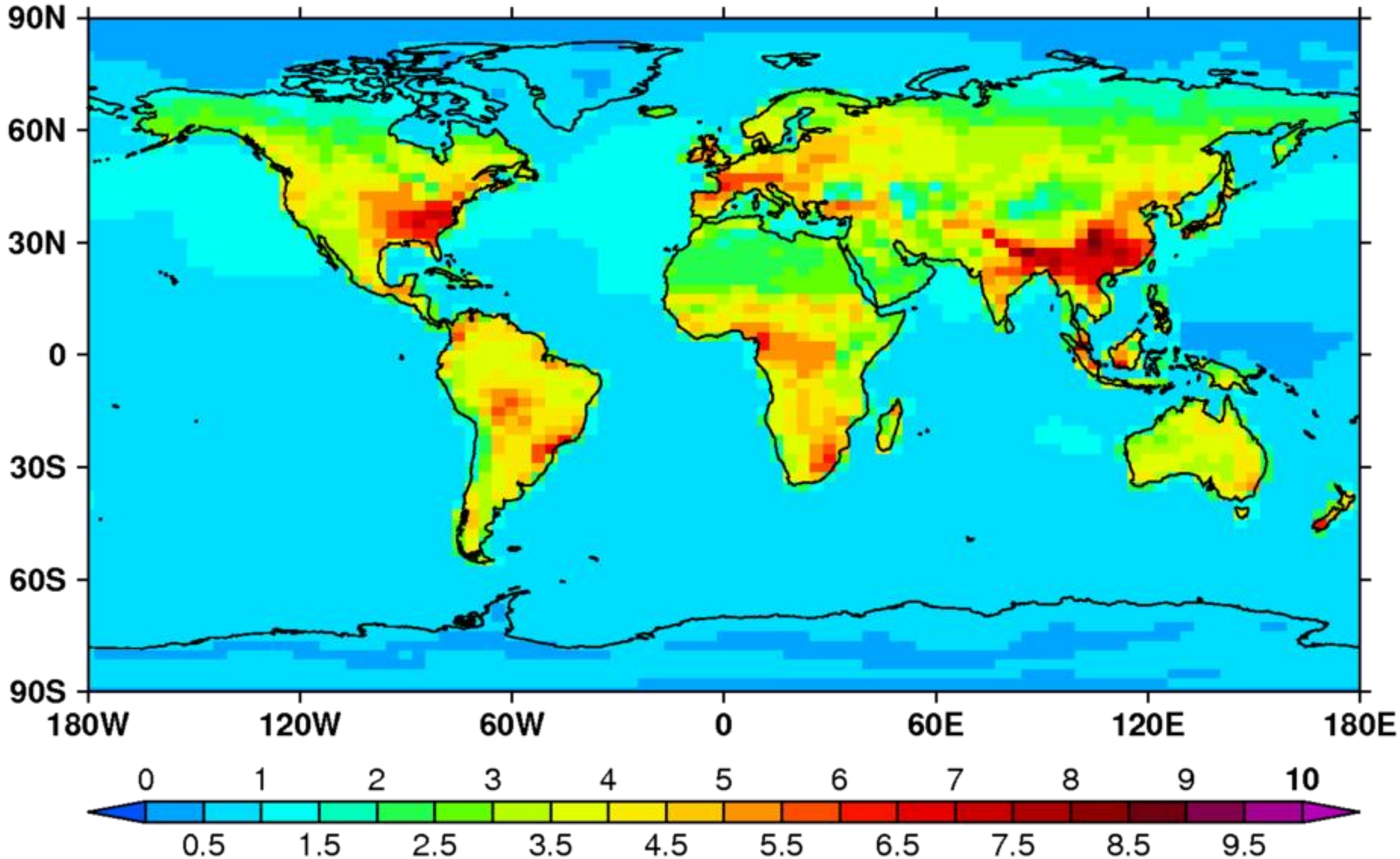
- What is dry deposition?
- Why is it interesting/important?
- How is it represented in UKCA?
- Model improvements underway/planned
- Research questions related to dry deposition

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)

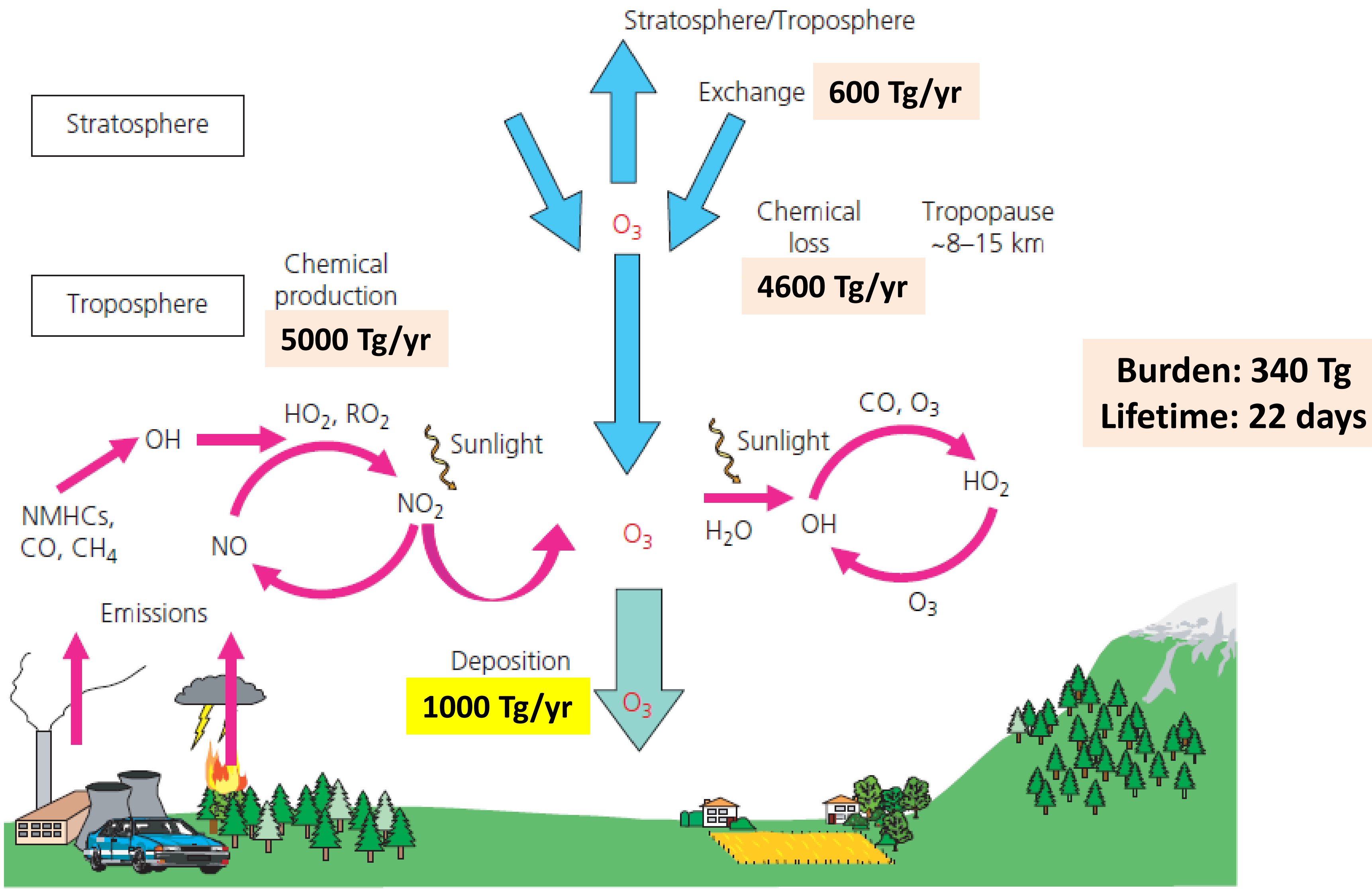
Annual mean O_3 deposition flux

(Year 2000, UKCA vn7.3)



Units TBD!

Sources/sinks of tropospheric ozone (yr 2000)



Stevenson et al 2006; Royal Society, 2008

O_3 dry deposition 'velocities' in the HTAP models

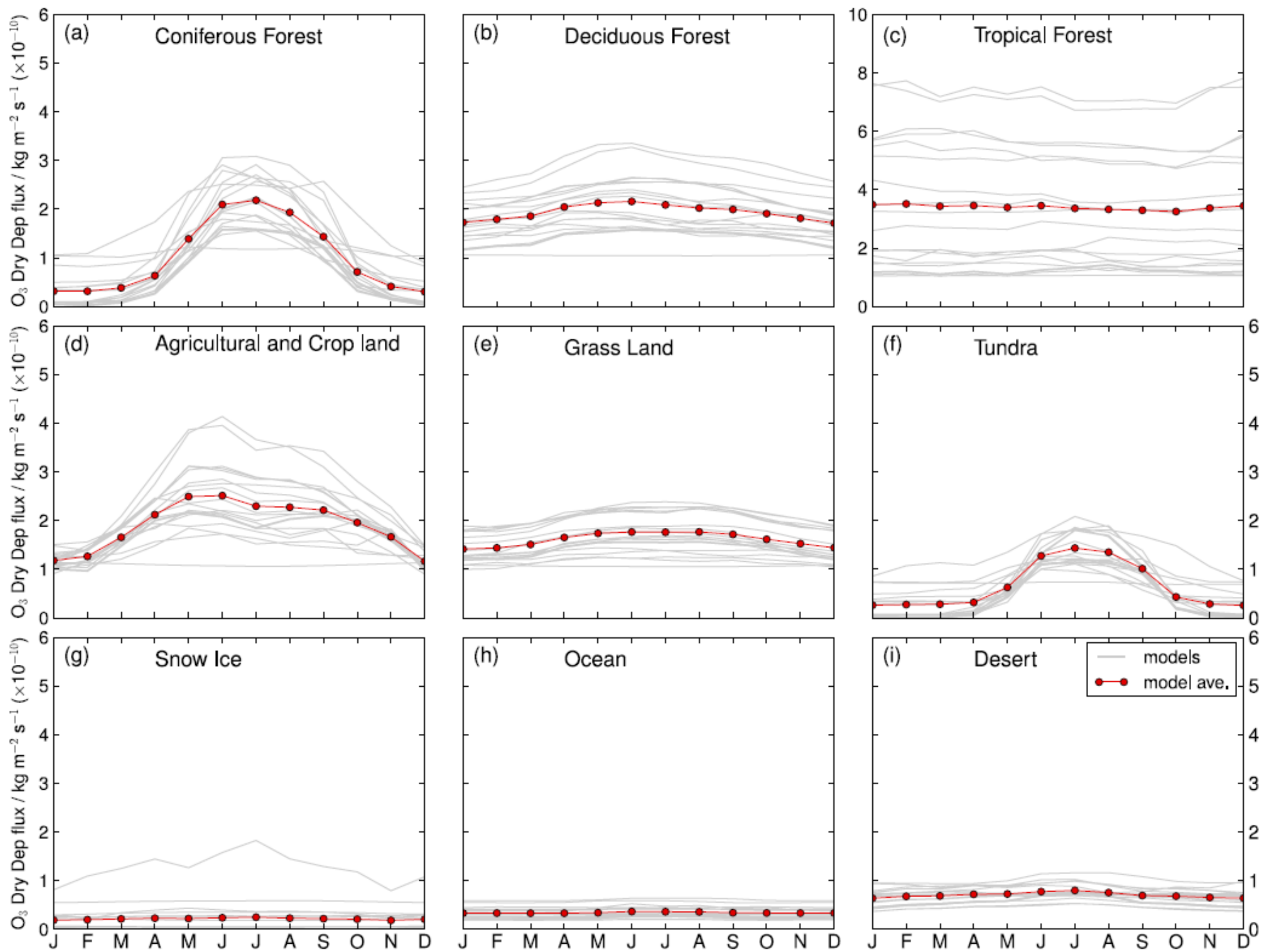


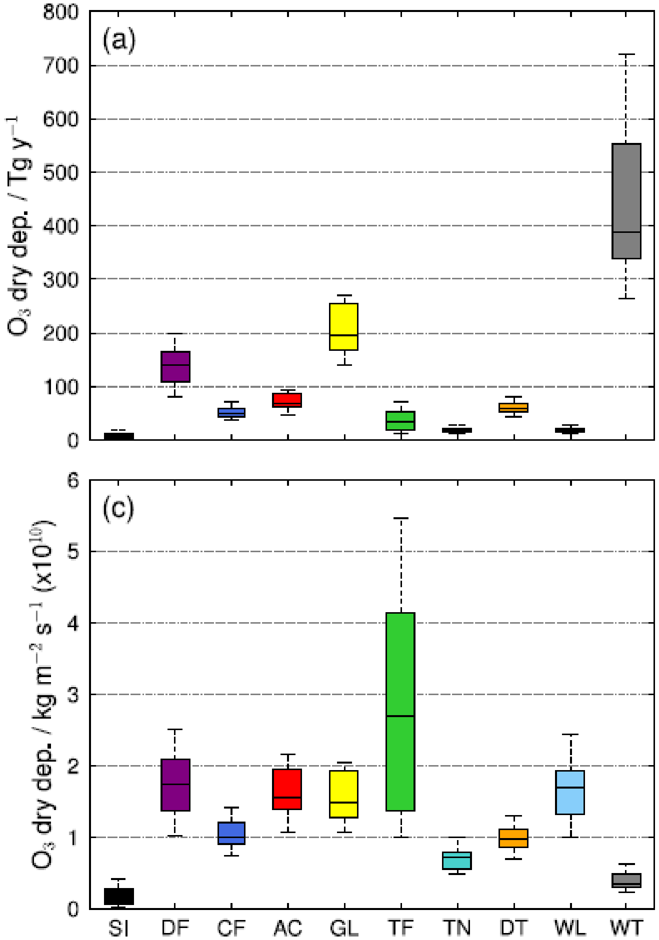
Figure 3. Normalised average monthly O_3 dry deposition at grid cells with 100 % land cover class coverage. Model fluxes are shown in grey and the ensemble average in red.

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

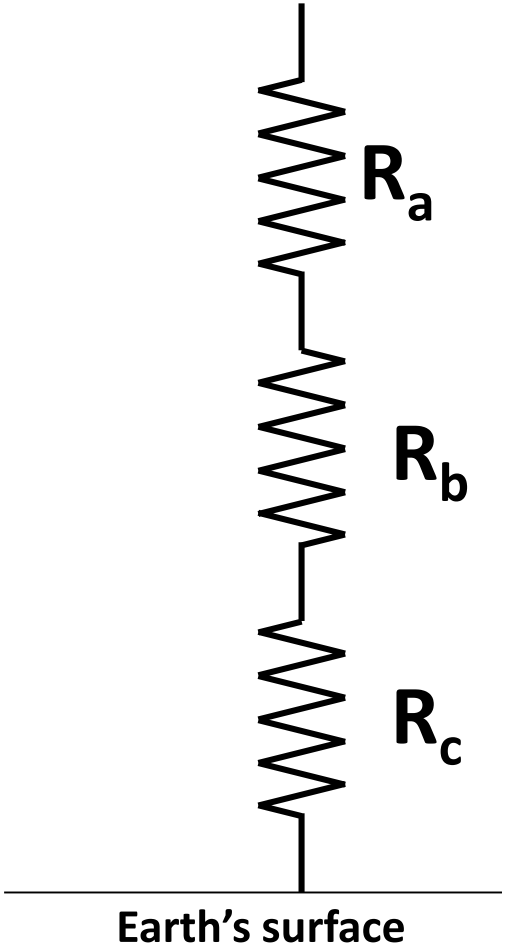
Deposition velocity:

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

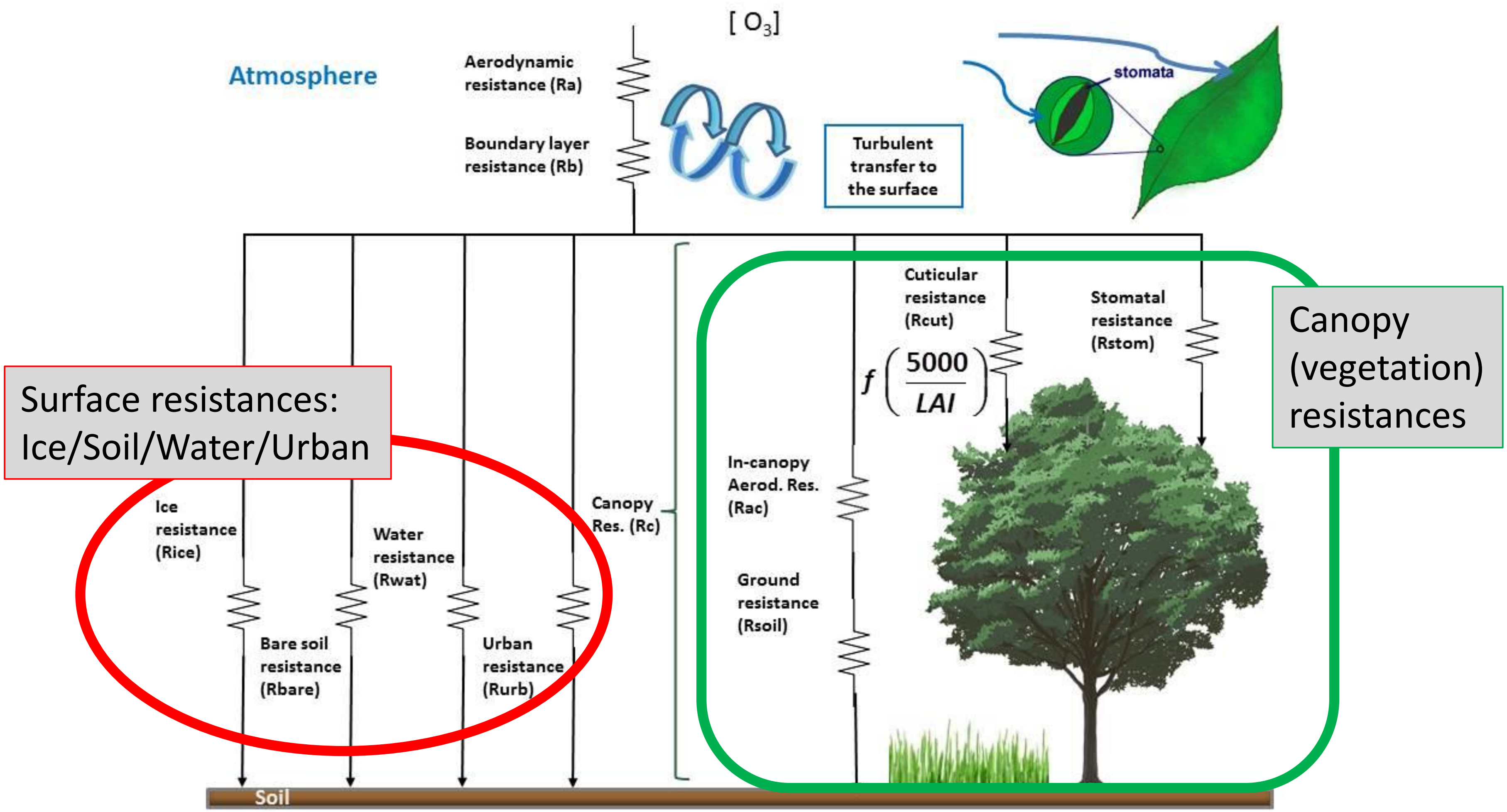
$= \text{Flux/Concentration (at ref ht)}$

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

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



Expanded surface/canopy resistance terms

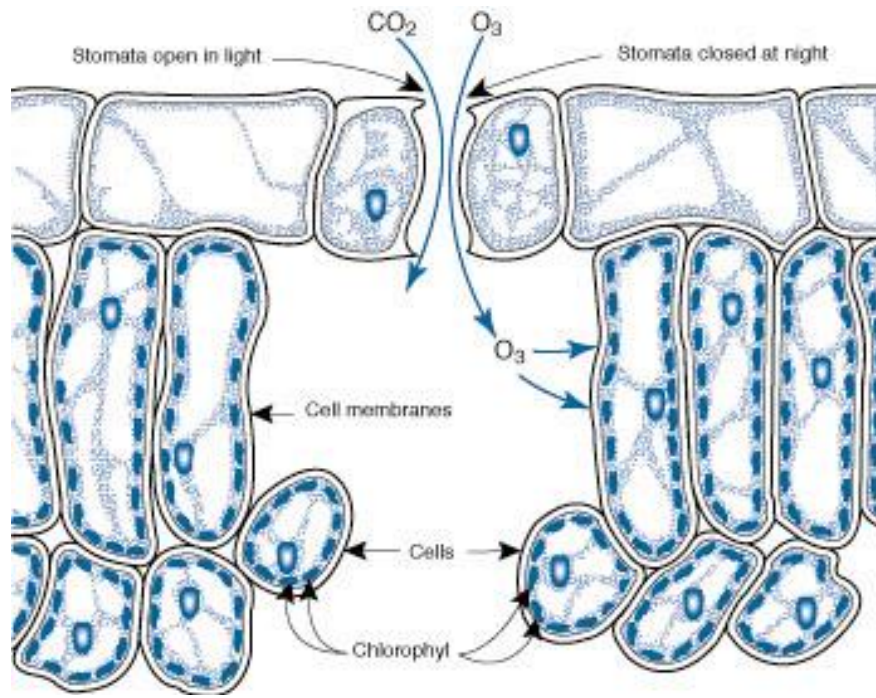


Federico Centoni, after Wesely (1989)

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

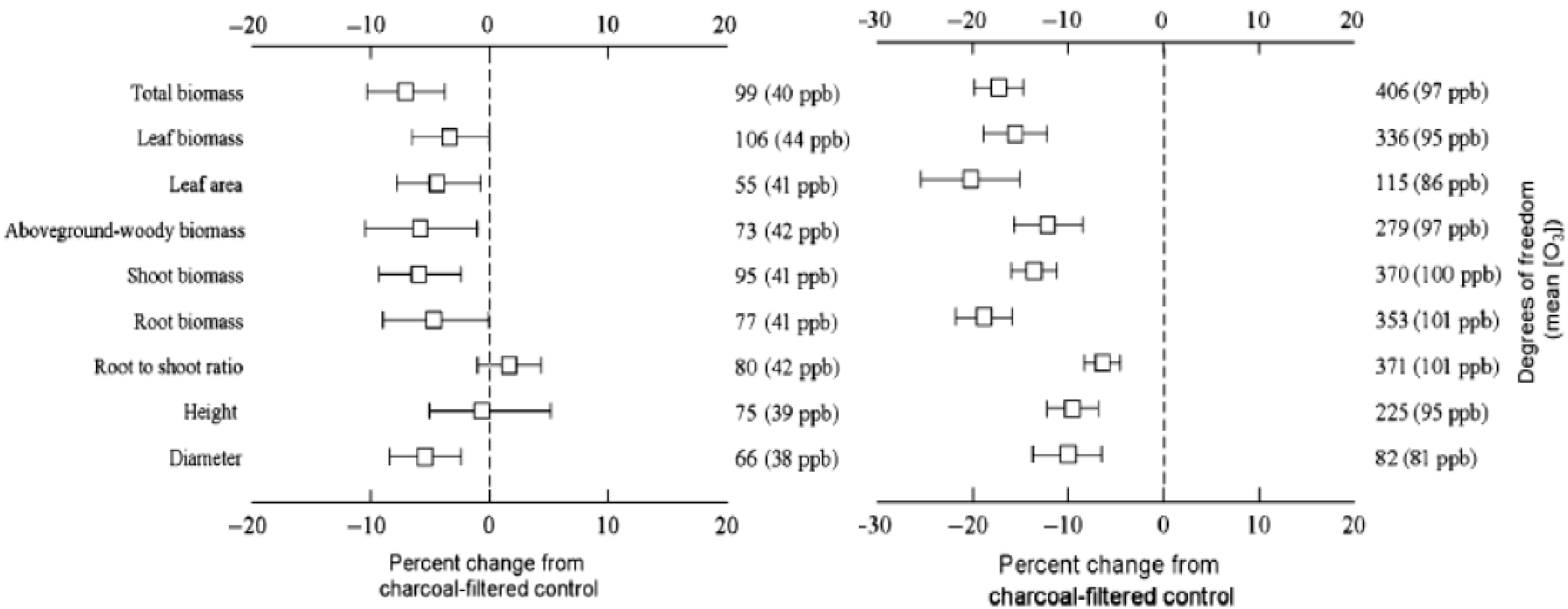
'FACE' experiments (Free Air CO_2 enrichment)

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

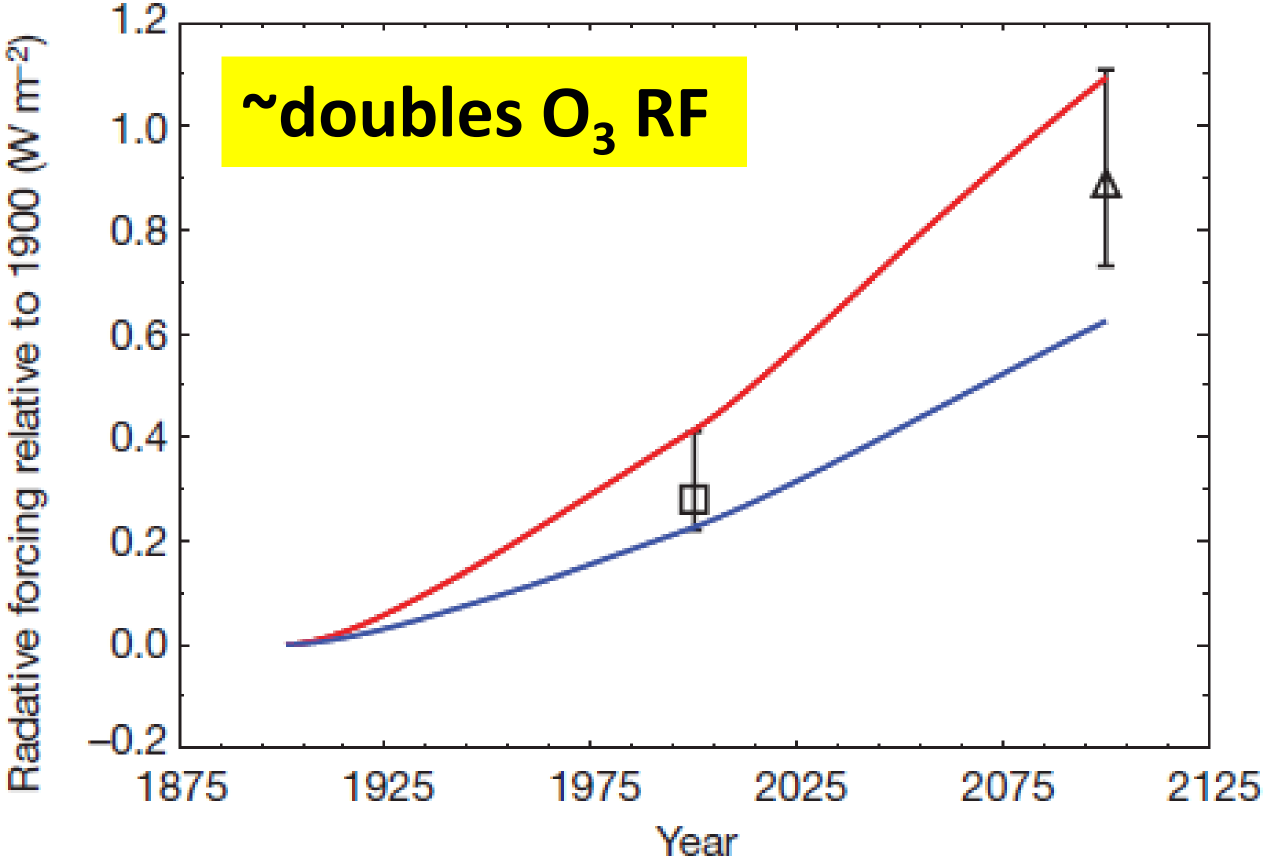
VICTORIA E. WITTIG*, ELIZABETH A. AINSWORTH*†, SHAWNA L. NAIDU‡, DAVID F. KARNOSKY§ and STEPHEN P. LONG*



Ozone impacts at ambient levels (~40 ppb)

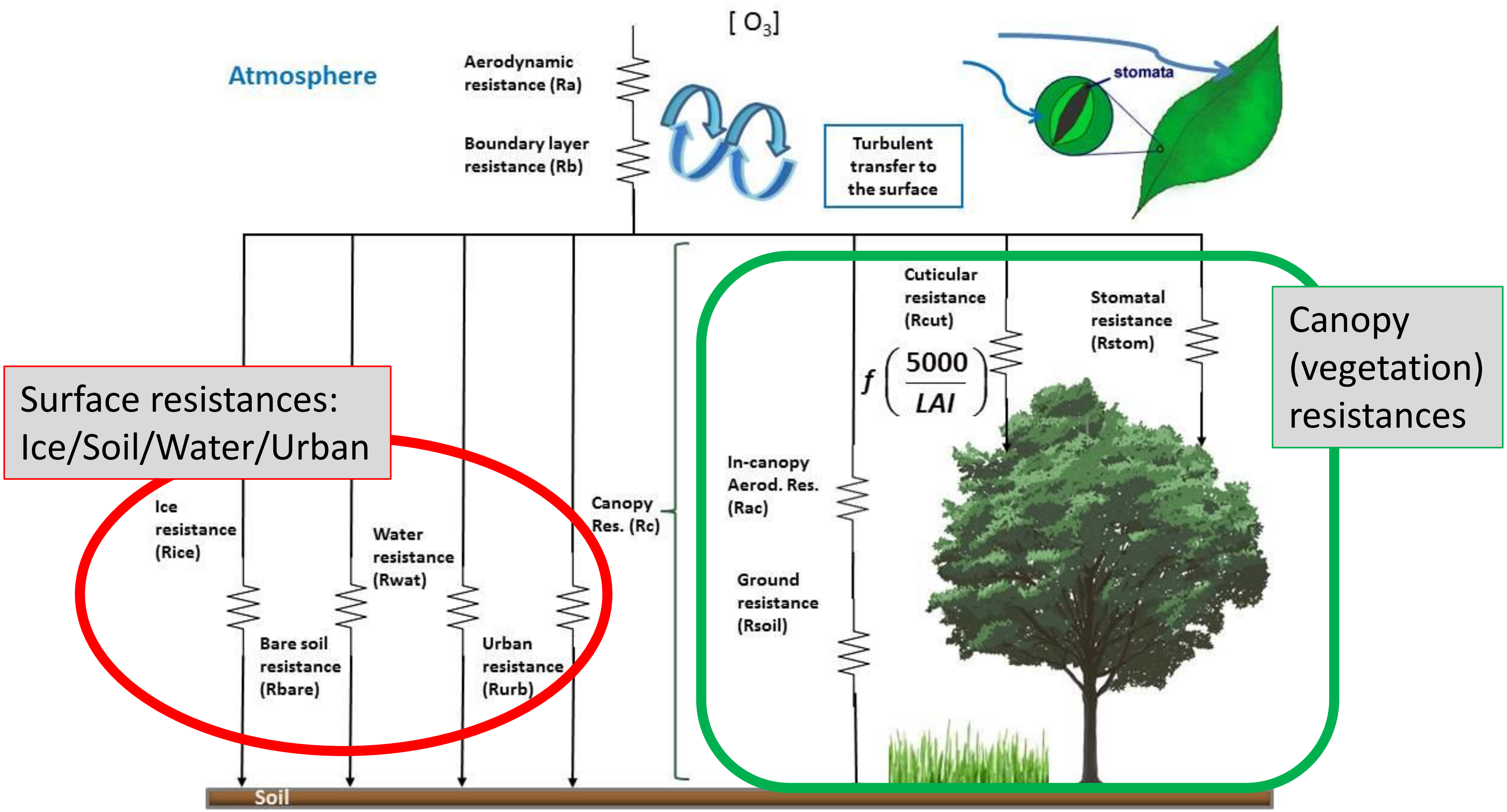
Ozone impacts at elevated levels (~80-100 ppb)

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.

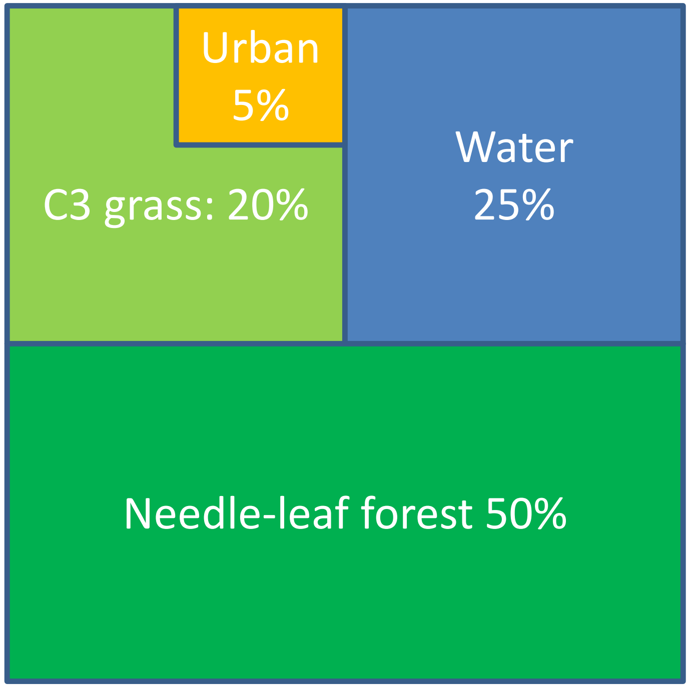
$$R_a = \left(\ln\left({}^{z}/_{z_0}\right) - \varphi\right)/ku_*$$

- 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	
MPAN	
CO	CO
CH4	CH_4
NH3	NH_3
SO2	SO_2
DMSO	
MSA	
OnitU	
SEC_ORG	Any other secondary organics
ORGNIT	Organic nitrogen

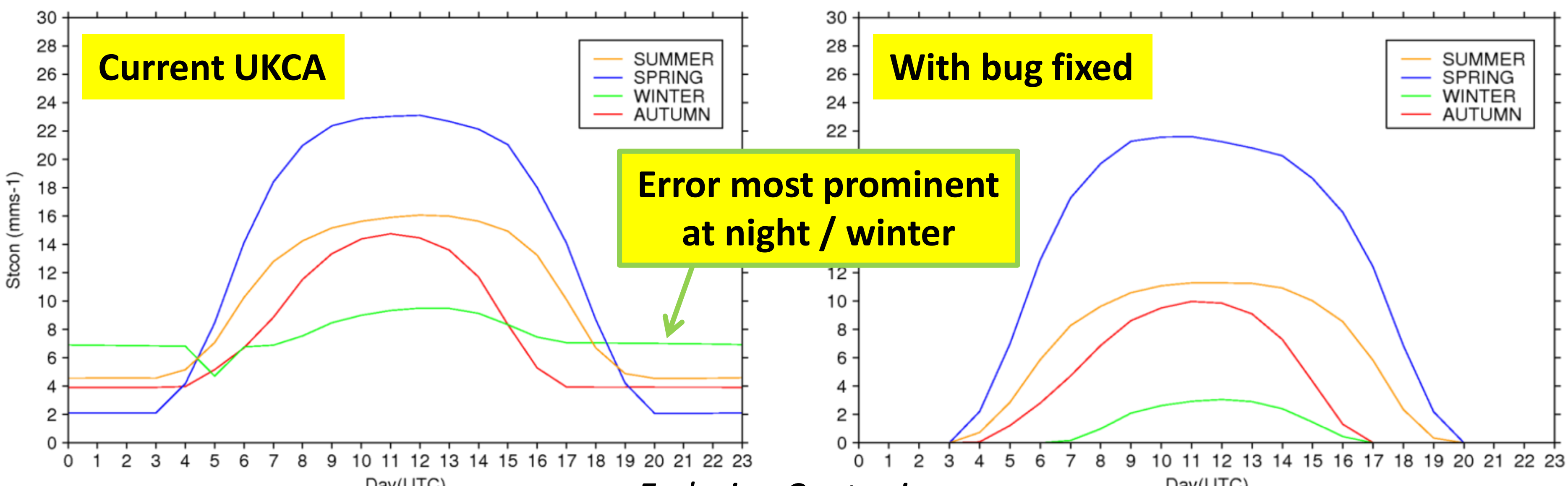
Examples to follow focus on ozone, but NB many species dry deposited

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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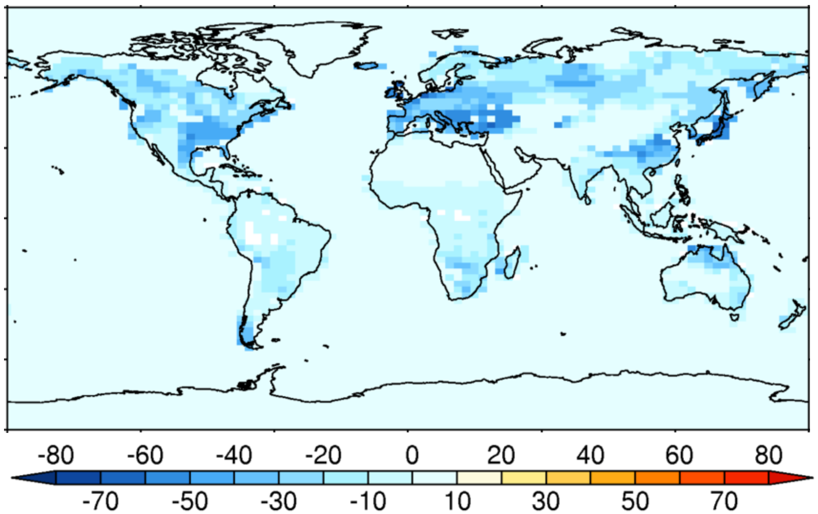
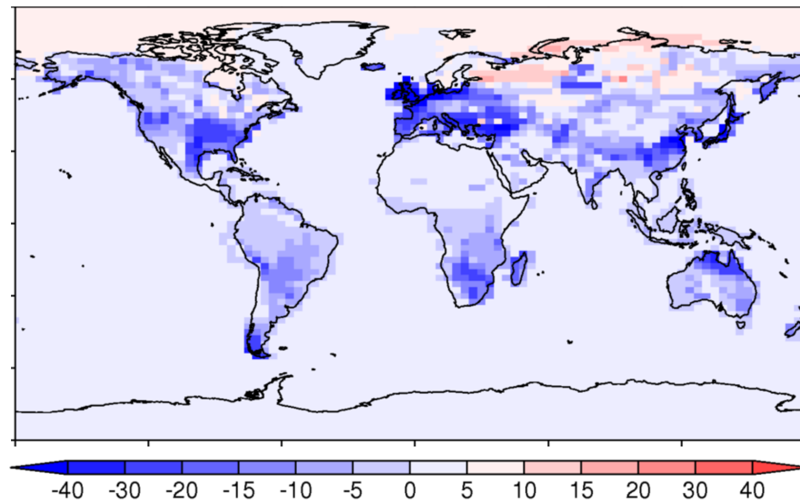
Global impact of the stomatal bug fix

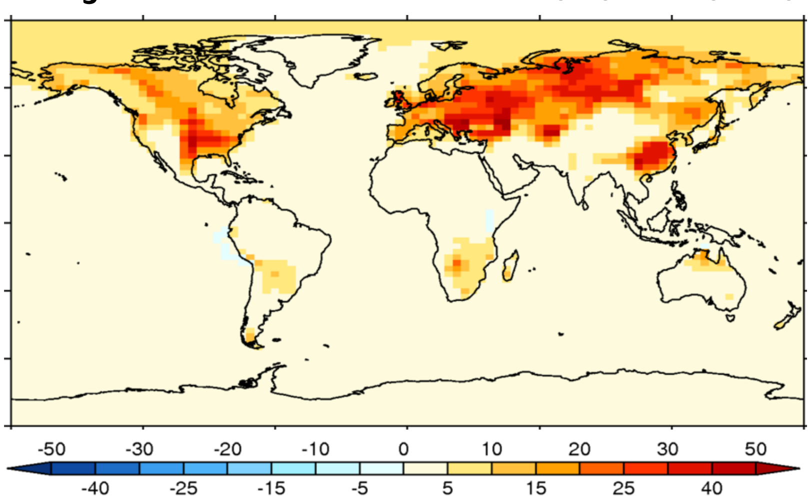
ΔO_3 deposition velocity (%) **(Jan)**



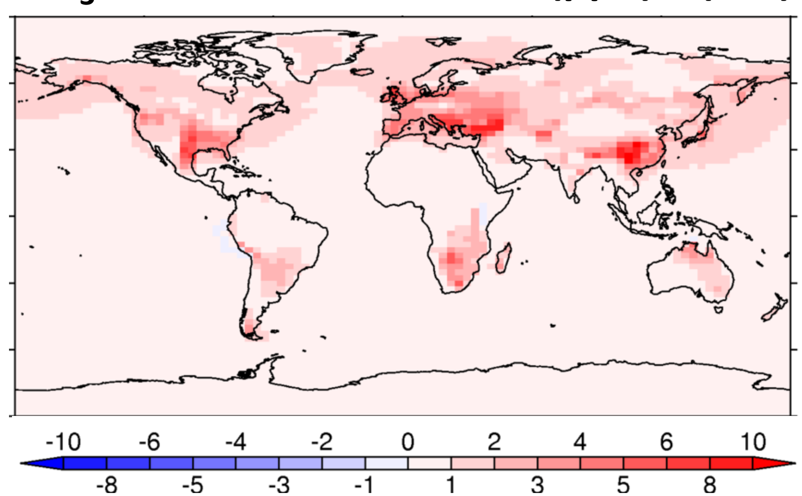
ΔO_3 deposition flux (%) **(Jan)**



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



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



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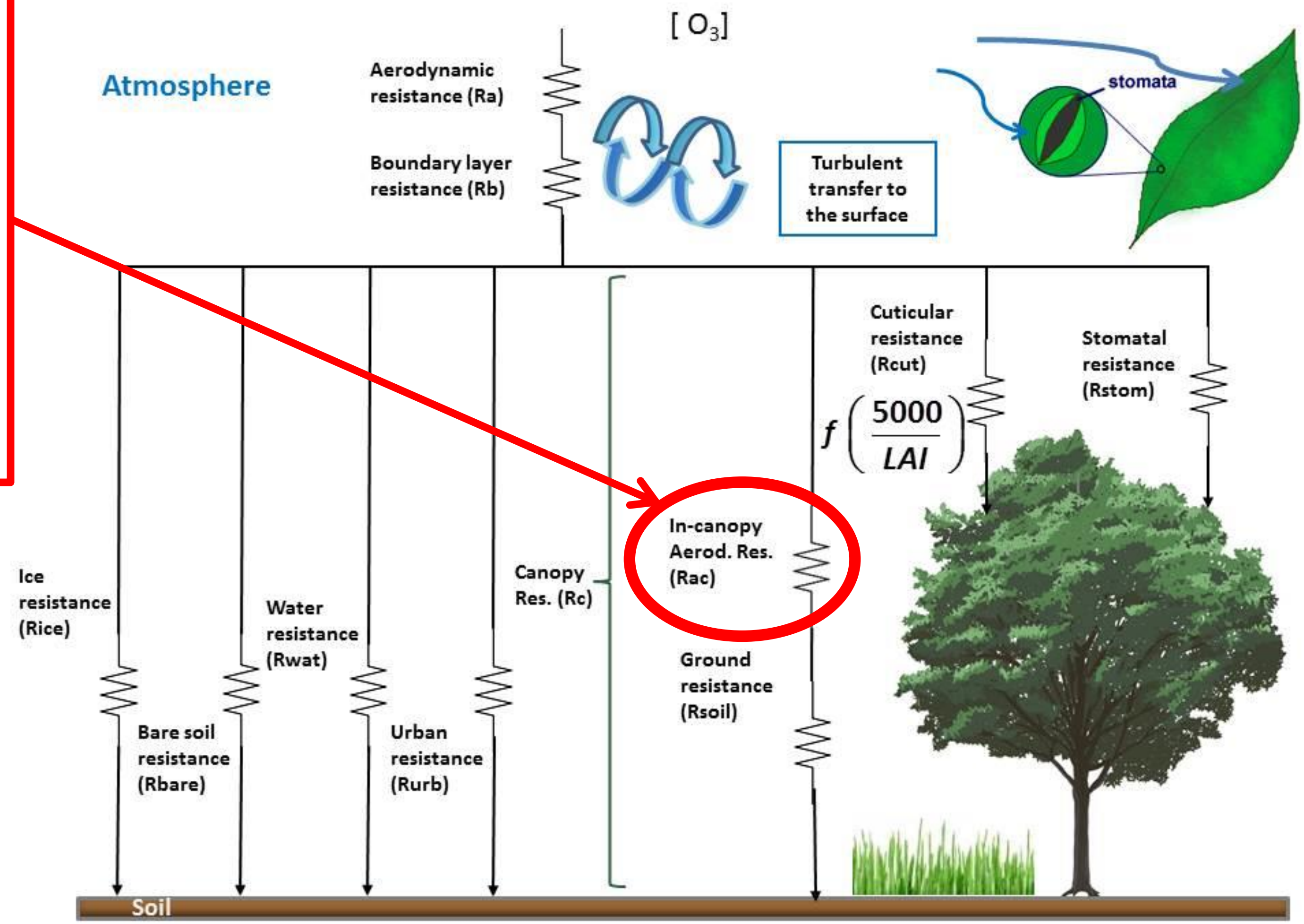
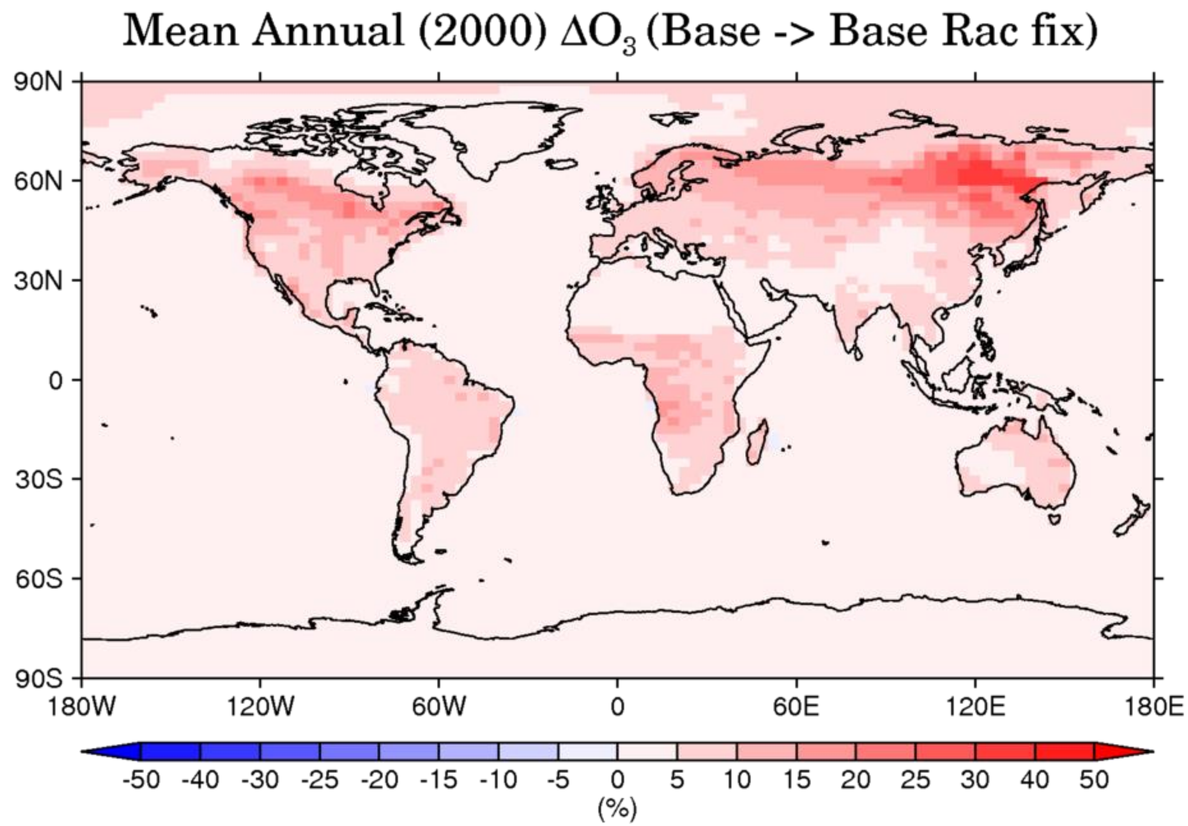
Bug fix 2: In-canopy resistance

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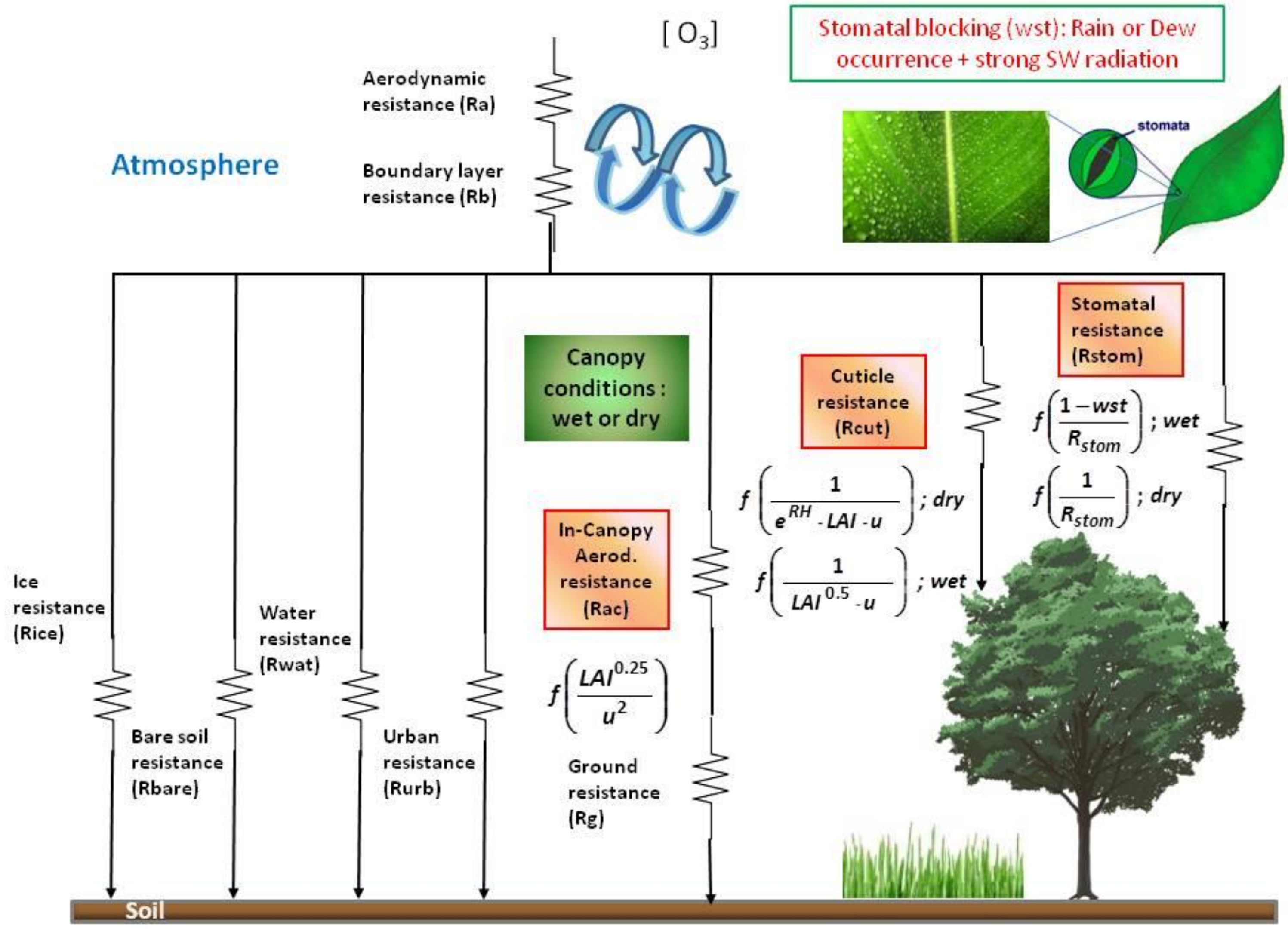
Adding the resistance term reduces deposition, particularly over forests, so O_3 concentrations increase.
[Caveat: I am unsure if R_{ac} terms still need to be added for all species:
I think here only the O_3 R_{ac} terms have been added; this is probably important.]

Further code developments: Zhang et al. (2003)



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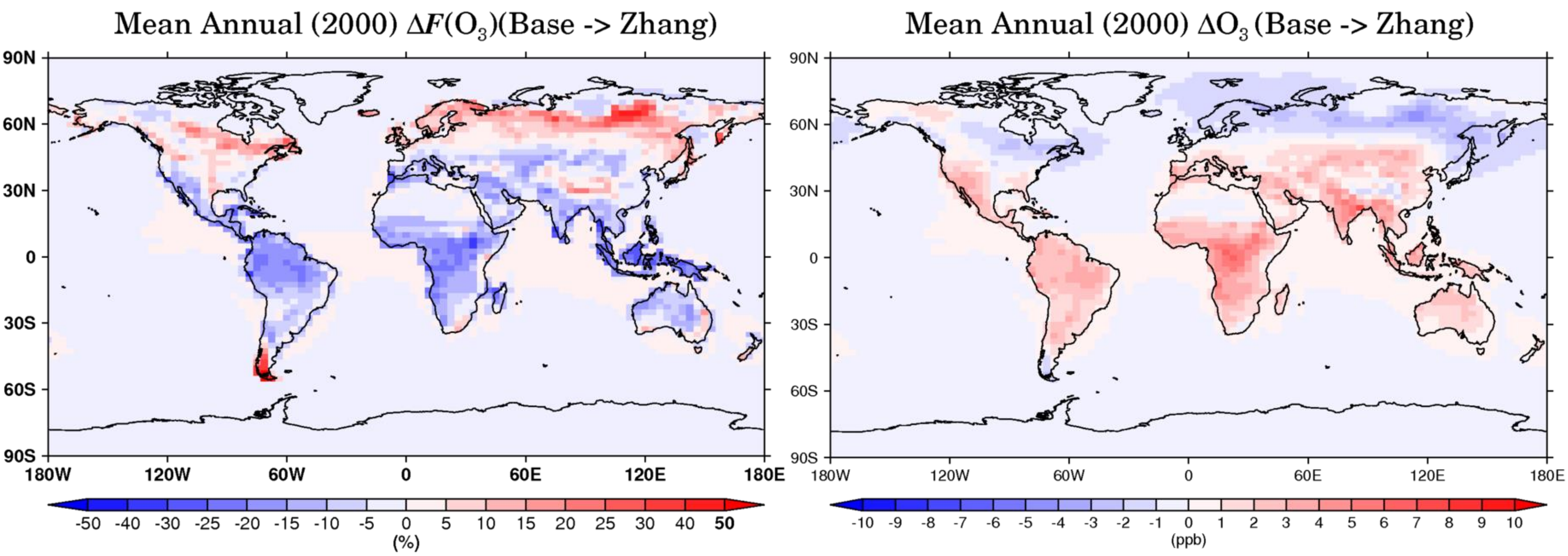
Impacts of Zhang et al scheme on O_3 deposition flux & surface O_3 concentration



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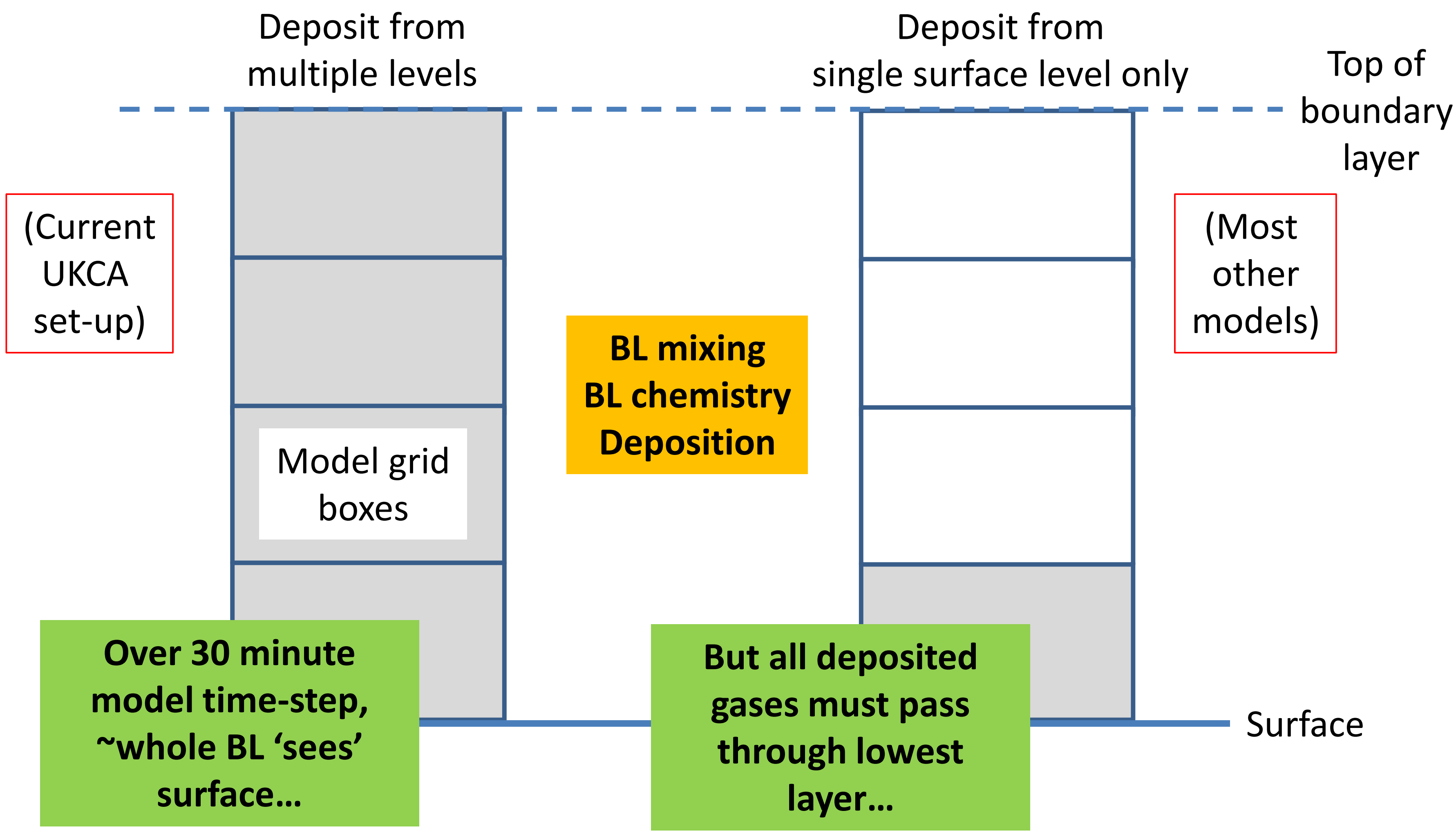
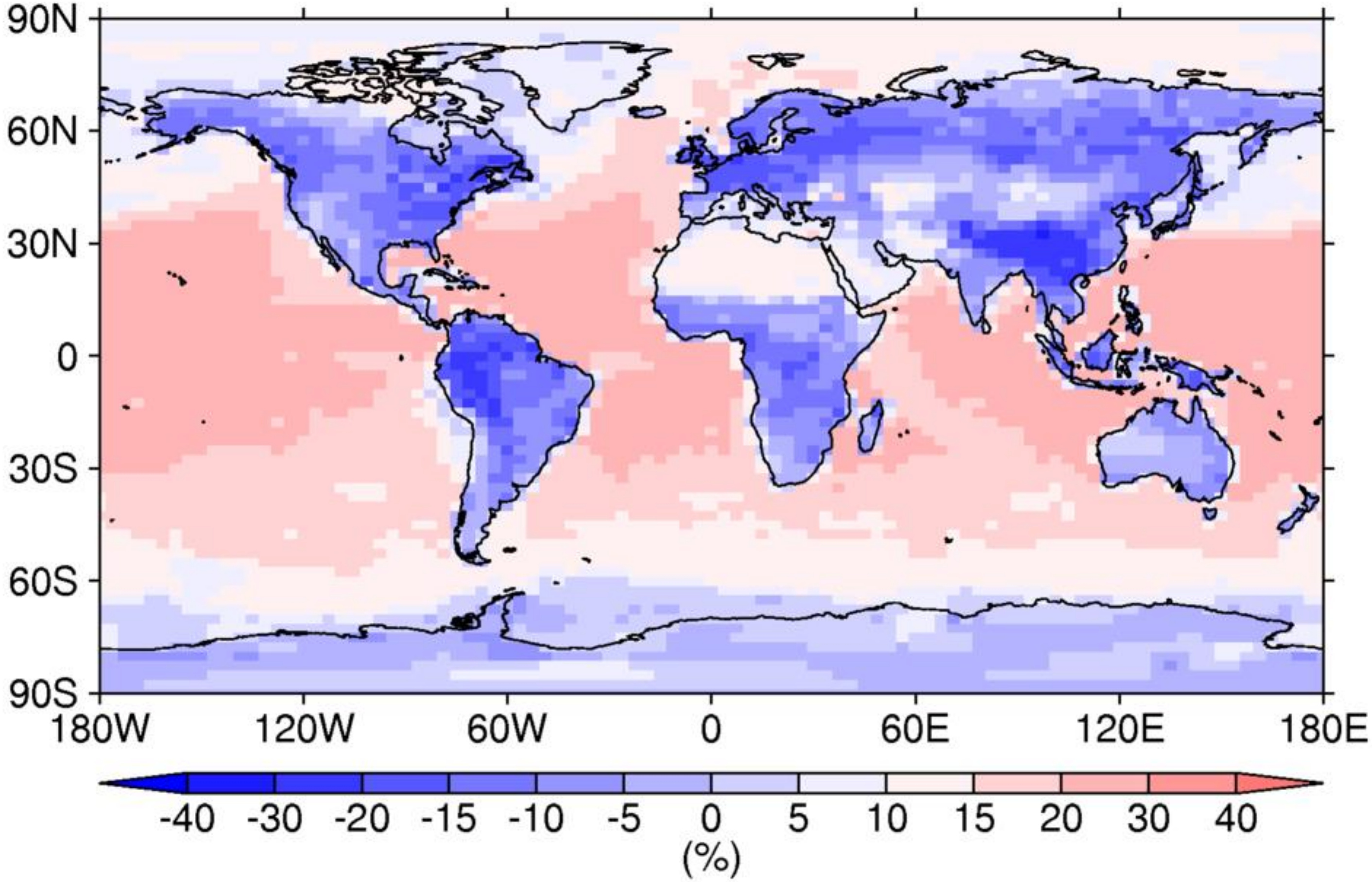
Currently evaluating whether the Zhang scheme improves comparisons with observations

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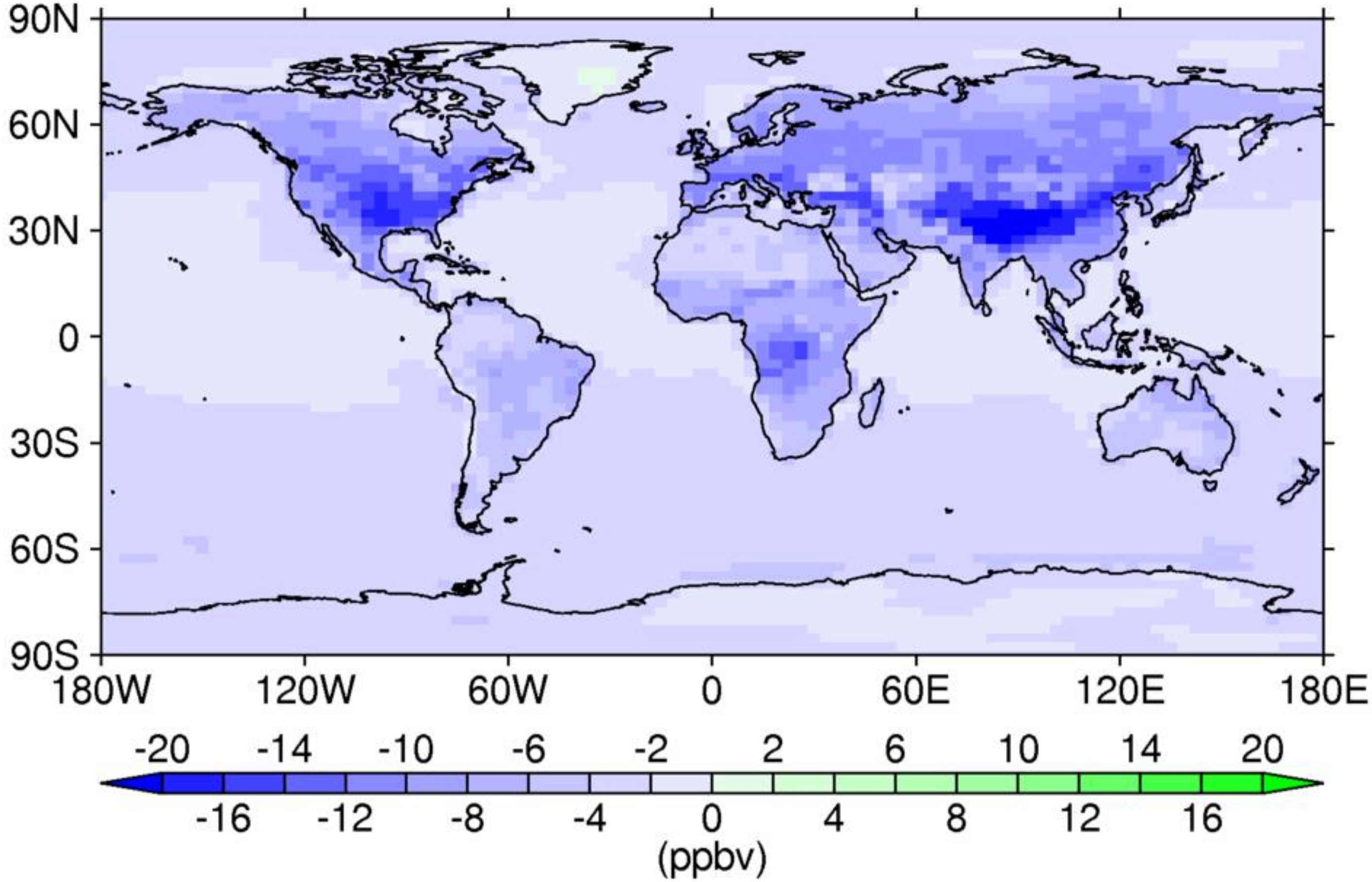
Global total O_3 dep flux remains at ~1100 Tg/yr

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.)