Imperial College London

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Climate Change and the Environment
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Photolysis processes
and how we model them

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NERC SCIENCE OF THE ENVIRONMENT

Aims & Objectives

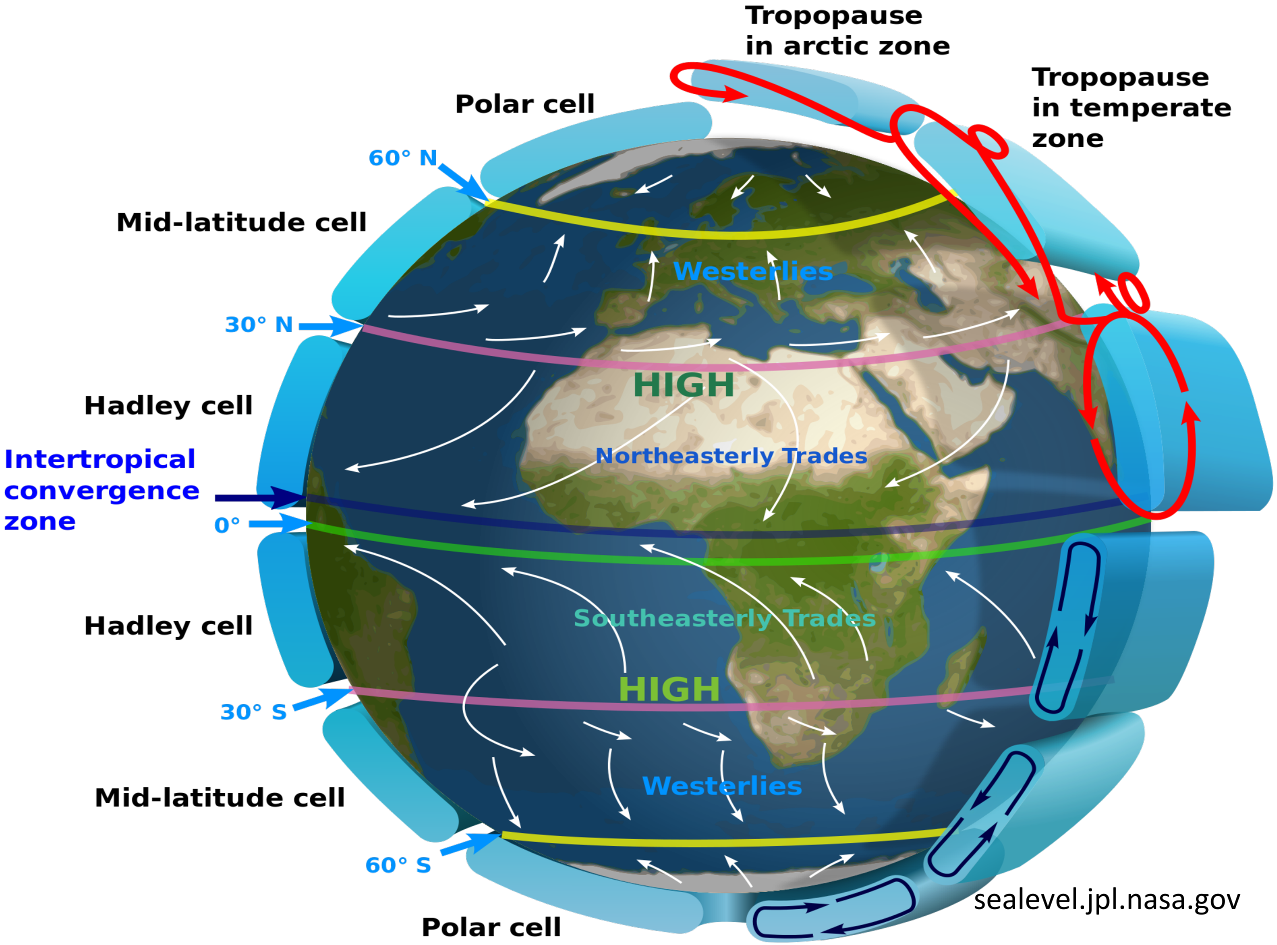
- Establish why photolysis processes are of central importance in atmospheric chemistry.

- Describe the main quantities needed for calculating photolysis rates of constituents.

- Provide a basic overview of the features of the Fast-JX photolysis scheme, used in UKCA.

- Describe some photolysis-focused science that has been pursued using the Fast-J family of modules, either in UKCA or in other global models.

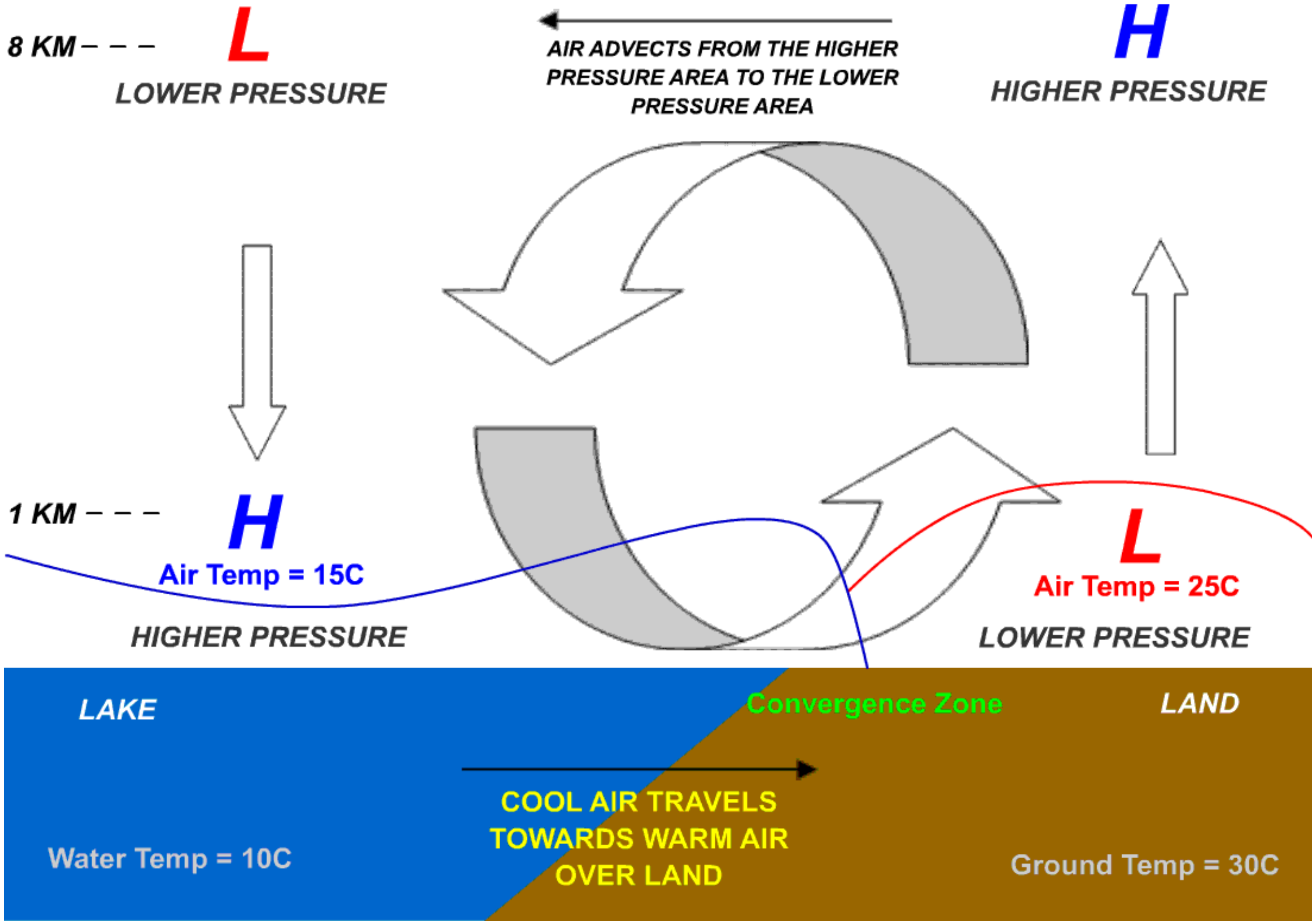
Solar Radiation: The driving force behind global circulation and large-scale weather



sealevel.jpl.nasa.gov

- Meridional insolation & temperature gradients drive the zonal mean atmospheric circulation, the position of storm tracks, and, thus, weather.

Solar Radiation: The driving force behind regional/local circulation



en.wikipedia.org/wiki/Sea_breeze

- Land-sea thermal contrasts drive regional circulations such as monsoons, and local circulations such as sea breezes.

But simultaneously: Solar radiation is the driving force behind atmospheric chemistry

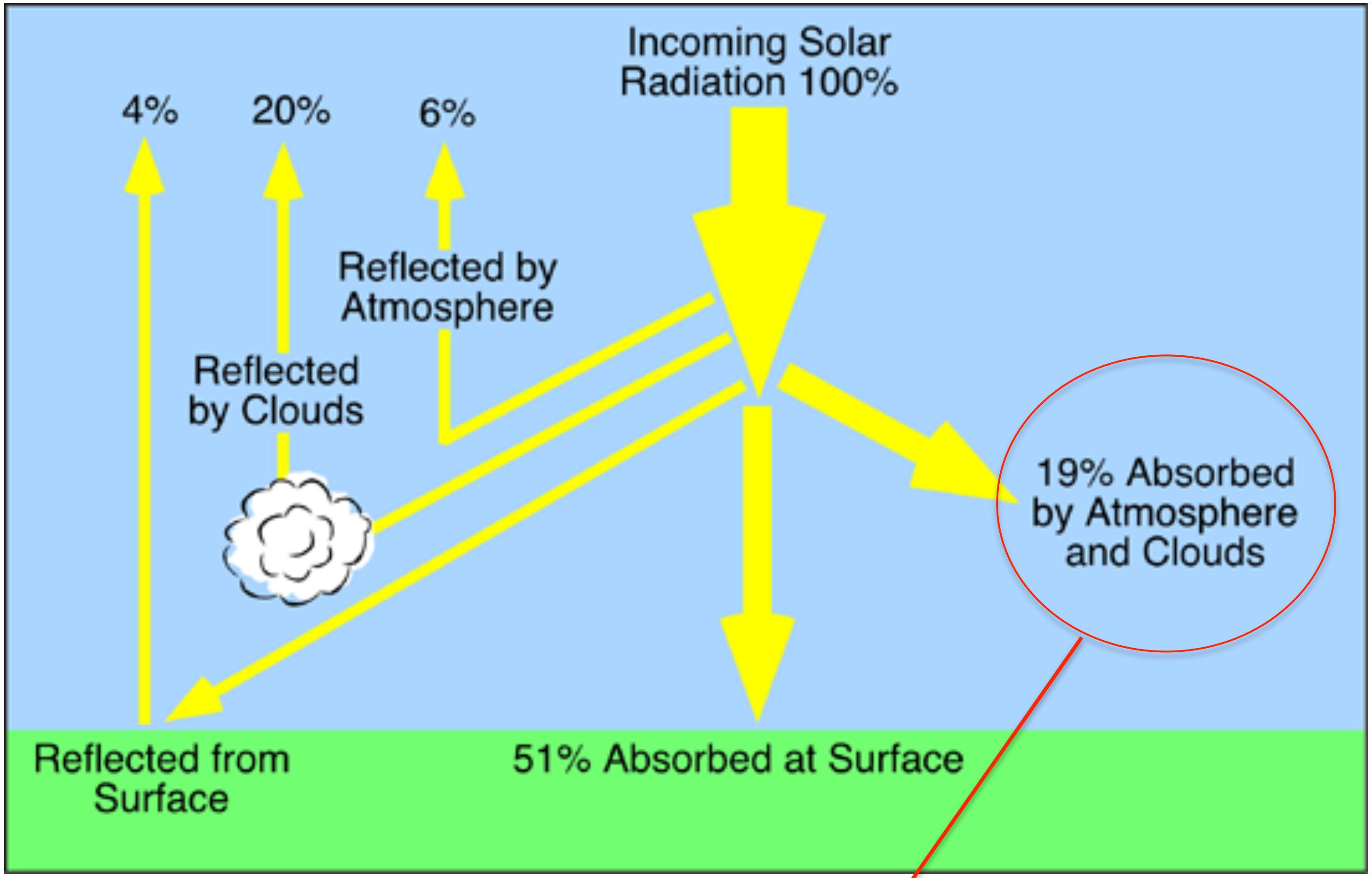
$$\frac{\partial E}{\partial t} = -\nabla \bullet (\mathbf{U}E) + \rho_A \frac{\theta_V}{T_V} \frac{dQ}{dt}$$

- The thermodynamic equation solved for each point in space (model gridpoints) and time (model timesteps) simulates the change of heat, and eventually of temperature, which influences the rates of many key chemical reactions.

- Changes in temperature cause changes in other meteorological variables such as humidity, rainfall, winds, turbulence, lightning, all of which strongly influence atmospheric chemistry.

- **But the most direct and crucial way in which solar radiation influences atmospheric chemistry is through driving photolysis (also called photodissociation).**

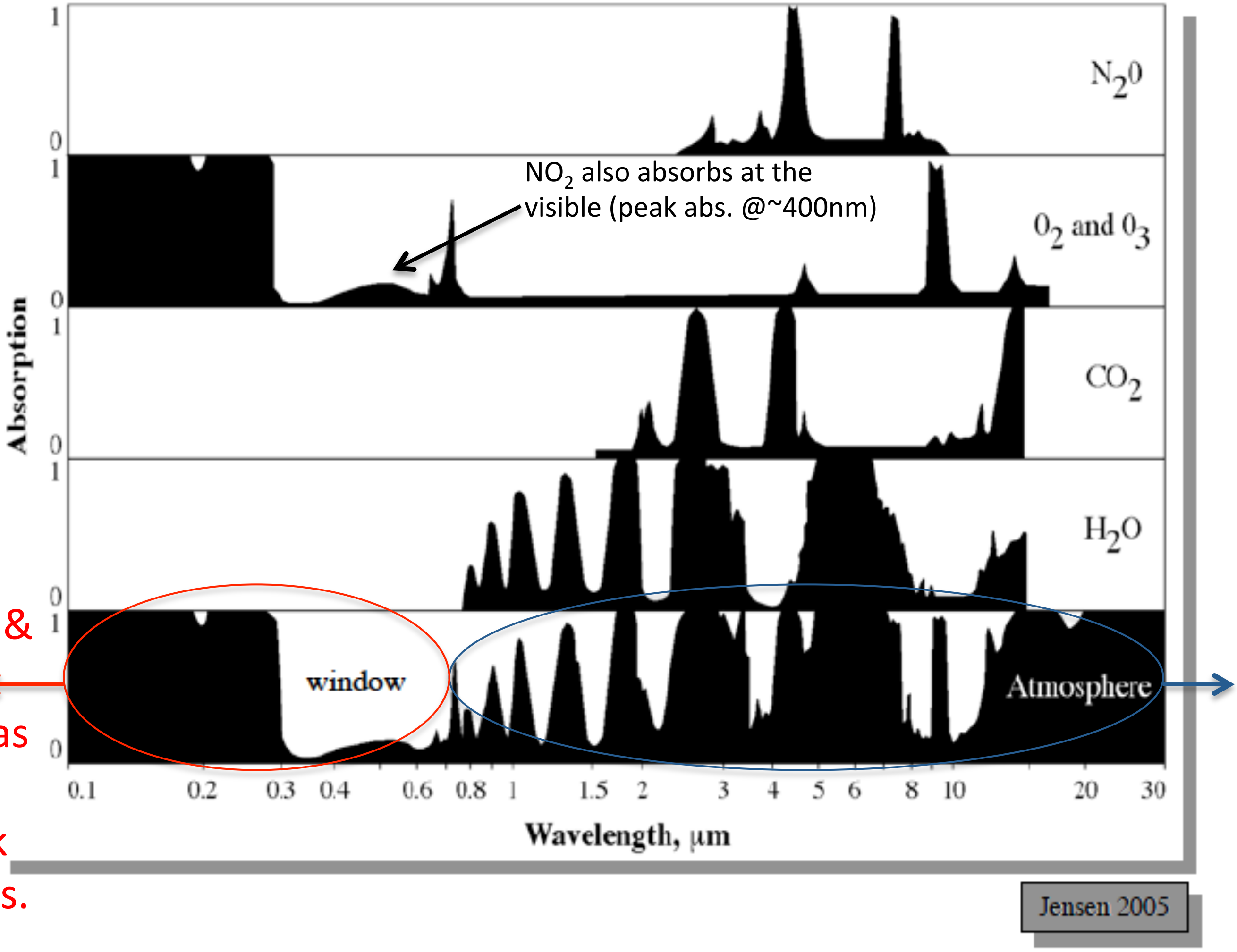
Radiative transfer in the atmosphere



www.physicalgeography.net

- This absorbed radiation is the cause of photolysis.
- GCMs include a radiative transfer module for climate.
- CTMs include a radiative transfer module for chemistry (photolysis scheme).
- CCMs include two codes for both (not very efficient!)

Absorption of the Sun's incident electromagnetic energy in the region from 0.1 to 30 µm (100-30,000 nm) by various atmospheric gases



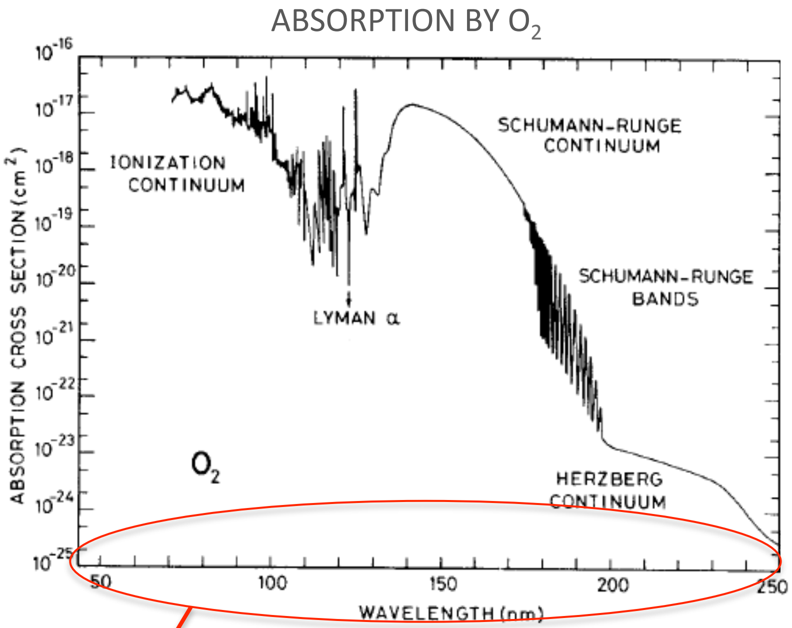
NO_2 also absorbs at the visible (peak abs. @~400nm)

Jensen 2005

Shortwave (UV & visible): key for photolysis, as it has enough energy to break down molecules.

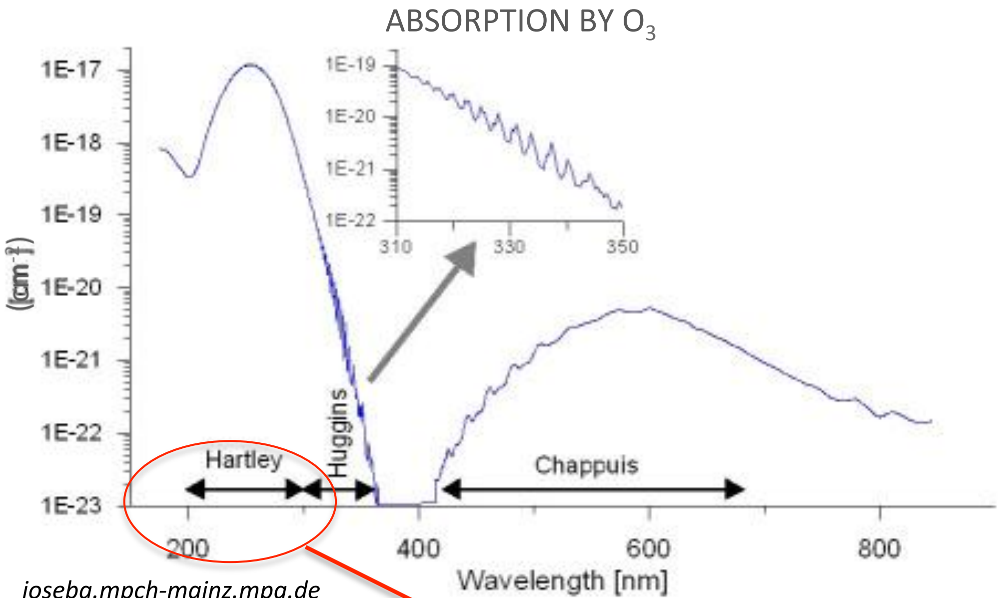
Longwave (solar + thermal IR): directly climate-relevant (esp. through coupling with vibrational modes).

Absorption by key gases that can undergo photolysis



ABSORPTION BY O_2

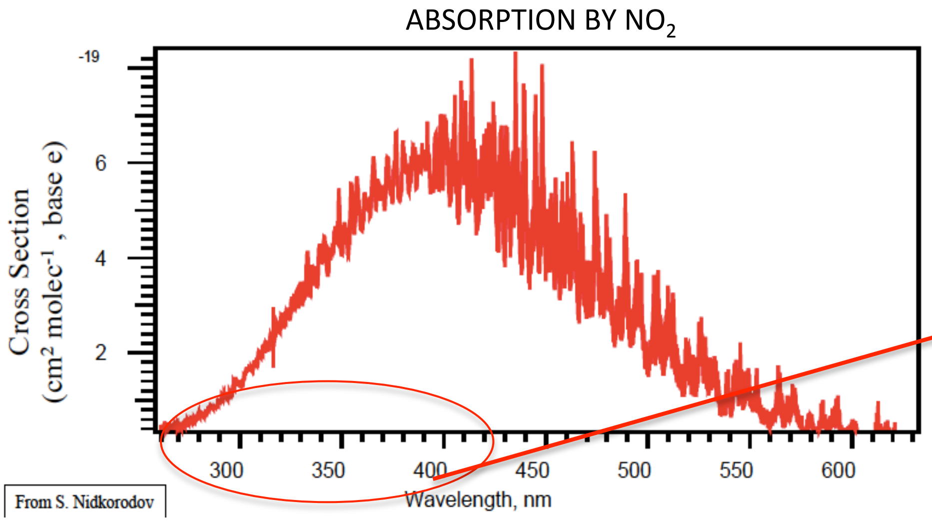
Very energetic wavelengths – not found in the troposphere (only slightly in the UT), but key for O_2 photolysis in stratosphere & mesosphere.



ABSORPTION BY O_3

joseba.mpch-mainz.mpg.de
Brasseur & Solomon (2005)
Jose-Luis Jimenez (2005)

Up to ~320nm, key for ozone (O_3) photolysis in the troposphere & stratosphere.



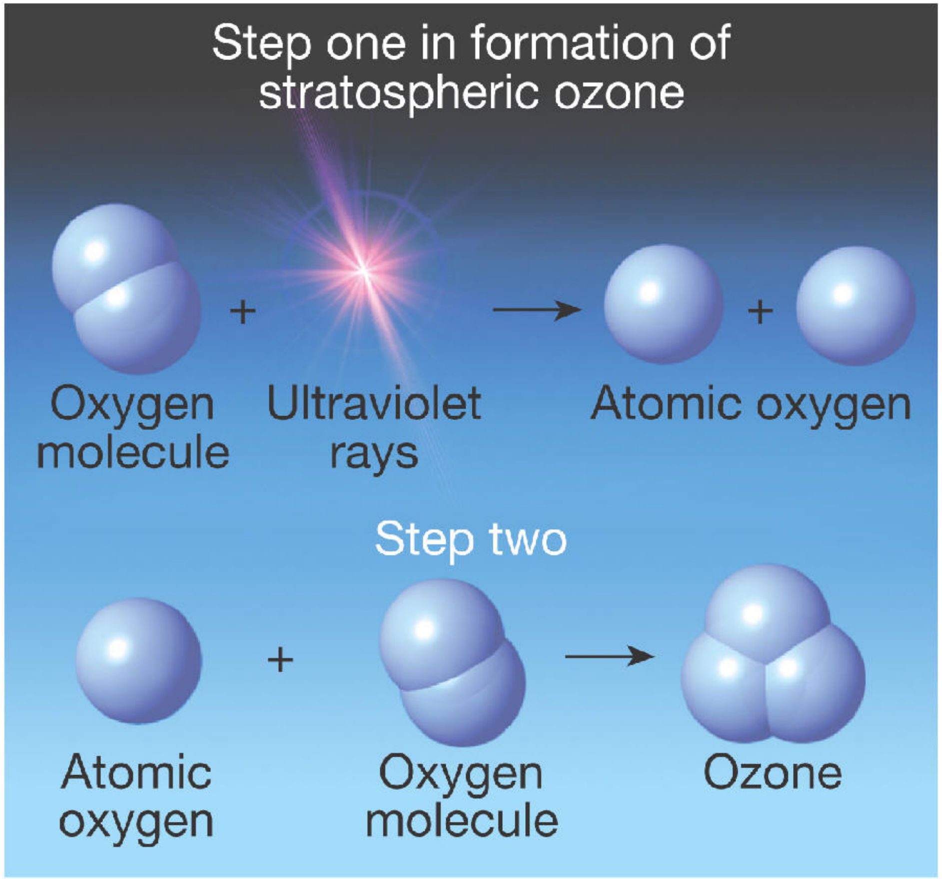
ABSORPTION BY NO_2

From S. Nidkorodov

Up to ~420nm, key for NO_2 photolysis in troposphere & stratosphere.

(*Note that x-sections are typically temperature dependent.)

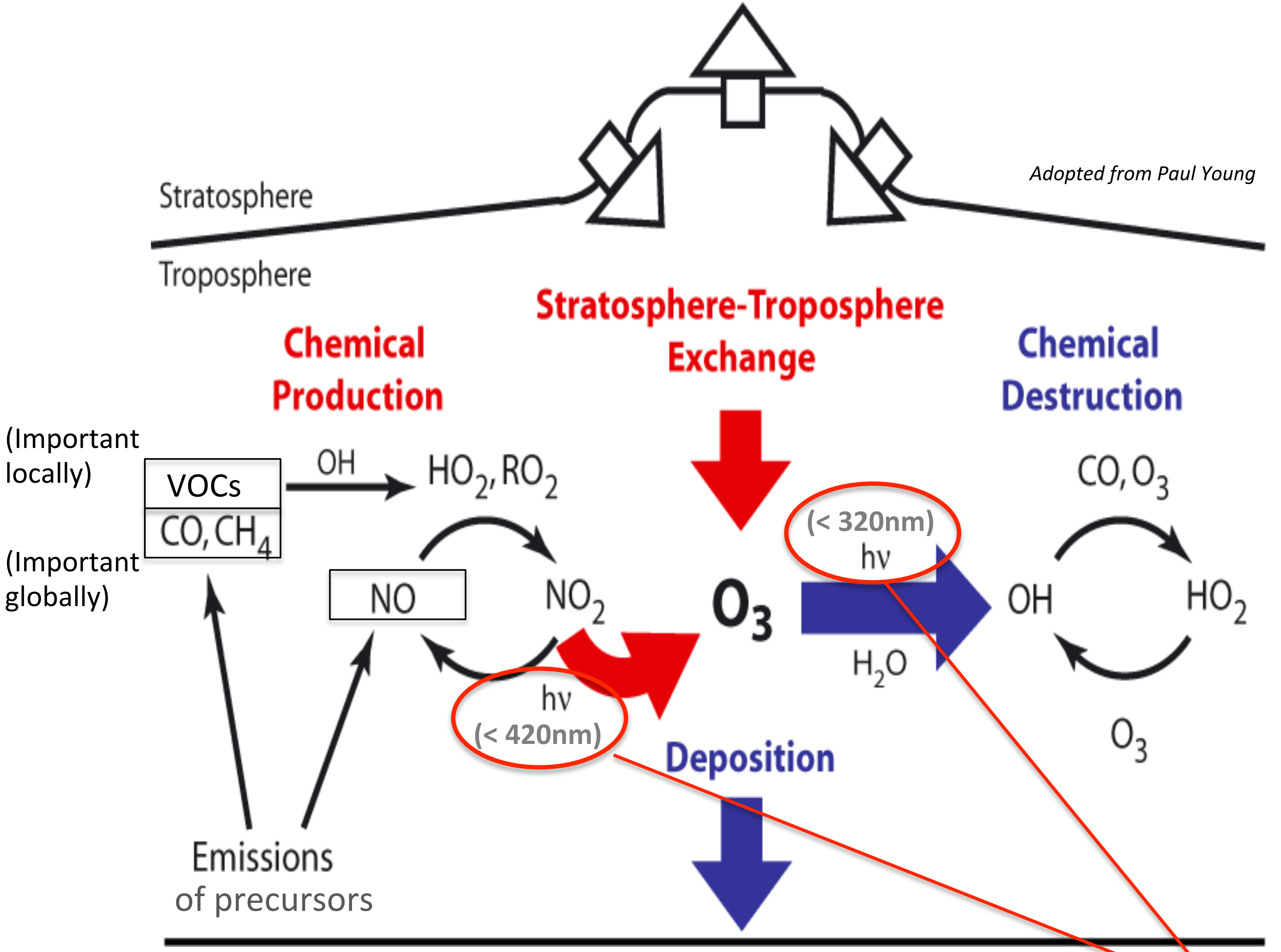
Photolysis and stratospheric ozone



www.geography.hunter.cuny.edu

- Highly energetic photons (<240 nm) break down O_2.
- Subsequently, atomic oxygen reacts with oxygen molecules to yield O_3.
- These two reactions are part of the Chapman mechanism.
- Photolysis is also key for catalytic ozone destruction (see later).

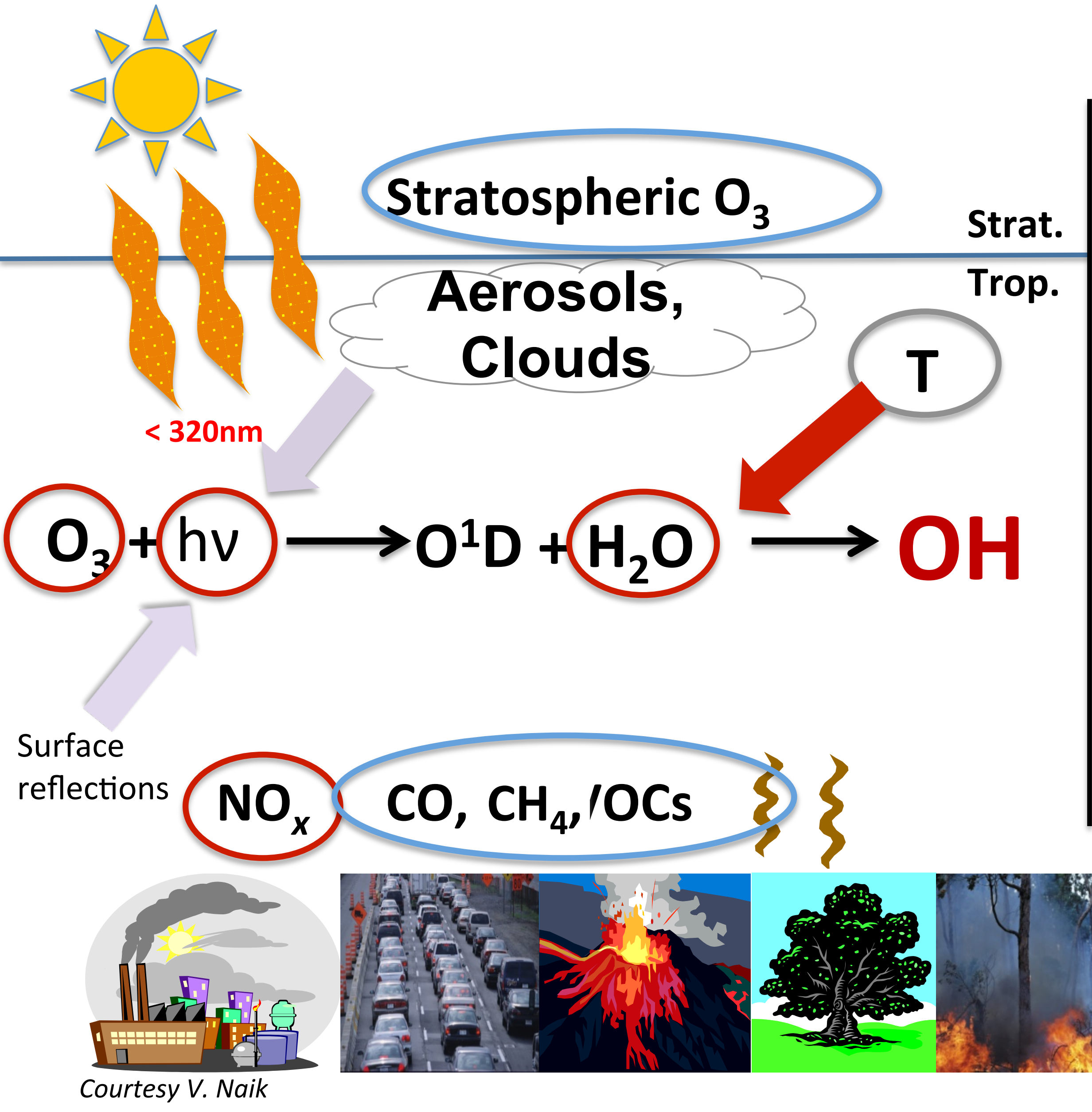
Photolysis and the tropospheric ozone budget



Adopted from Paul Young

Key role of photolysis in trop. O_3 production & loss.

Photolysis and the hydroxyl radical (OH)



Stratospheric O_3

Strat.

Trop.

Aerosols, Clouds

< 320nm

T

$O_3 + h\nu \longrightarrow O^1D + H_2O \longrightarrow$ **OH**

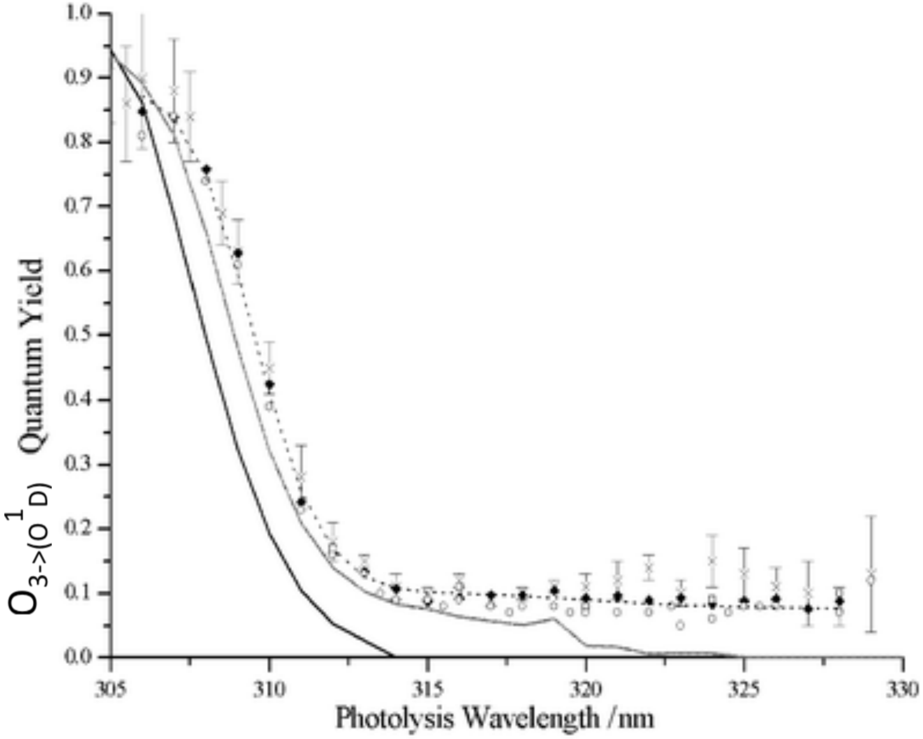
Surface reflections

NO_x CO, CH_4, VOCs

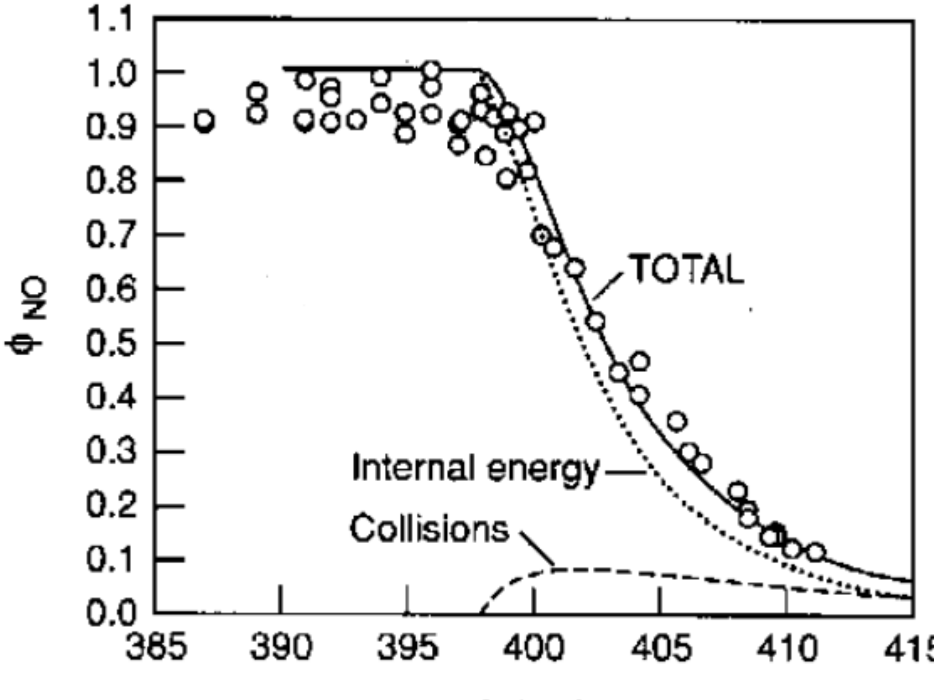
Courtesy V. Naik

- OH is a major tropospheric oxidant (detergent of the troposphere).
- It removes CO/VOCs, is involved in tropospheric ozone (O_3) production, and in aerosol formation.
- It is the major sink of CH_4 in the atmosphere: OH determines CH_4 lifetime.

How many molecules are photolysed per photon absorbed (the O_3->O(^{1}D) and NO_2->NO quantum yields (φ))



Hancock & Tyley (2001)

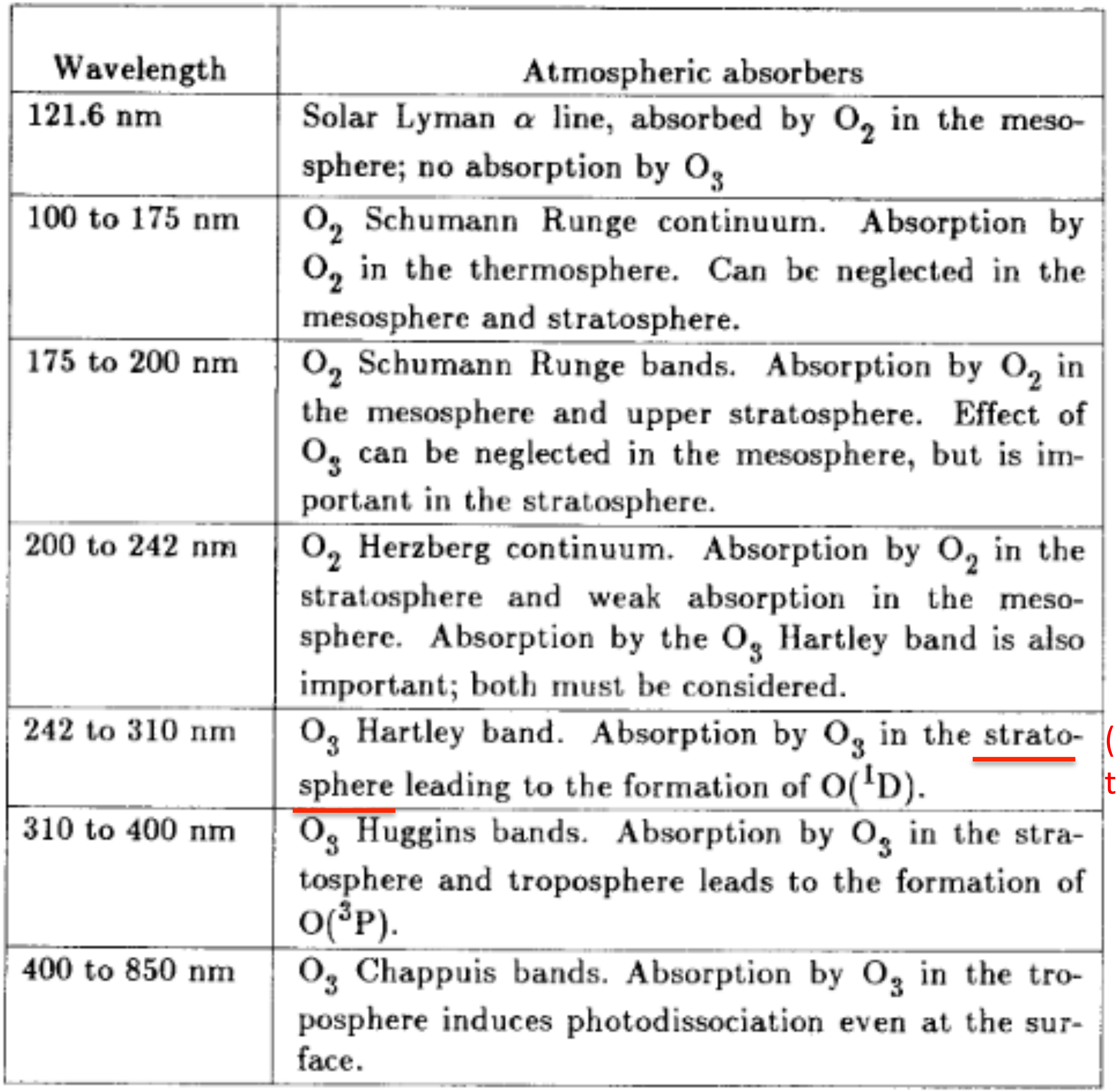


Jose-Luis Jimenez (2005)

- The “cut-off” for O_3 photolysis to produce O(^{1}D) is ~320-330nm, and for NO_2 photolysis to produce NO is ~420nm.
- Thus, upper wavelength limit set by quantum yield rather than by cross section.
- For O_2 photolysis it is absorption that sets the upper limit.

Summary of O_2 & O_3 Photochem.

Table 4.1 Spectral regions of photochemical importance in the atmosphere



Wavelength	Atmospheric absorbers
121.6 nm	Solar Lyman α line, absorbed by O_2 in the mesosphere; no absorption by O_3
100 to 175 nm	O_2 Schumann Runge continuum. Absorption by O_2 in the thermosphere. Can be neglected in the mesosphere and stratosphere.
175 to 200 nm	O_2 Schumann Runge bands. Absorption by O_2 in the mesosphere and upper stratosphere. Effect of O_3 can be neglected in the mesosphere, but is important in the stratosphere.
200 to 242 nm	O_2 Herzberg continuum. Absorption by O_2 in the stratosphere and weak absorption in the mesosphere. Absorption by the O_3 Hartley band is also important; both must be considered.
242 to 310 nm	O_3 Hartley band. Absorption by O_3 in the stratosphere leading to the formation of $O(^1D)$.
310 to 400 nm	O_3 Huggins bands. Absorption by O_3 in the stratosphere and troposphere leads to the formation of $O(^3P)$.
400 to 850 nm	O_3 Chappuis bands. Absorption by O_3 in the troposphere induces photodissociation even at the surface.

(and to some extent in the troposphere).

From Brasseur & Solomon

Summary of important photolysis reactions

- **$O_2 + h\nu \rightarrow O_2 + O(^3P)$ ($\lambda < 240$ nm)**

Initiates ozone production in stratosphere (and slightly in the upper trop.).

- **$O_3 + h\nu \rightarrow O_2 + O(^1D)$ ($\lambda < 320$ nm)**

Leads to ozone destruction and OH production.

- **$NO_2 + h\nu \rightarrow NO + O(^3P)$ ($\lambda < 420$ nm)**

Initiates ozone production in troposphere.

- **$HNO_3 + h\nu \rightarrow NO_2 + OH$ ($\lambda < 350$ nm)**

Main loss process of HNO_3 (which is a "NOx reservoir").

- **$HCHO + h\nu \rightarrow H + HCO$ ($\lambda < 340$ nm)**

Contributes to HO_x production (similar for CH_3CHO and higher aldehydes).

- **$H_2O_2 + h\nu \rightarrow 2OH$ ($\lambda < 350$ nm)**

Can contribute to OH production.

- **$N_2O + h\nu \rightarrow N_2 + O(^1D)$ ($\lambda < 200$ nm)**

Destroys N_2O; Subsequently, $N_2O+O(^1D)$ produces NO_x in the stratosphere.

- **$CFC11 + h\nu \rightarrow CFCl_2 + Cl$ ($\lambda < 250$ nm)**

Releases Cl that destroys ozone in the stratosphere (similarly for other Cl species).

The photolysis rate

- For a given molecule A being photolysed ($A + h\nu \rightarrow B + C$):

$$\boxed{d[A]/dt = -J_A[A] = -\int \sigma_A(\lambda)\, \varphi_A(\lambda)\, F(\lambda) d\lambda \times [A]}$$

→ J_A : First order photolysis rate constant (or frequency) of A (s^{-1}).

→ $\sigma_A(\lambda)$: Absorption cross section, i.e. probability of a photon to be absorbed (cm^2/molec.).

→ $\varphi_A(\lambda)$: Quantum yield, i.e. number of molecules photolysed per photon absorbed (unitless).

→ $F(\lambda)$: Solar actinic flux, i.e. radiative flux from all directions (quanta $cm^{-2}\ s^{-1}$).

Lifetime with respect to photolysis

- The rate at which a chemical species A (with concentration *[A]*) is lost from the atmosphere is characterised by its *e*-folding lifetime τ_A.
- It is the time required by a gas to decrease to *1/e* its original concentration due to chemical reaction. Lifetimes are independent of emission/production rates.
- For example, for photolysis reaction:

$$\tau_A = \frac{1}{J_A} = \frac{[A]}{d[A]/dt}$$

- If concentration of a constituent is determined by multiple processes (1, 2,…, n), the overall lifetime is:

$$\tau_A = \frac{1}{\frac{1}{\tau_{A1}} + \frac{1}{\tau_{A2}} + \ldots + \frac{1}{\tau_{An}}}$$

The FAST- JX photolysis scheme *(Wild et al., 2000; Bian and Prather, 2002; Neu et al., 2007)*, **used in UKCA**

- Calculates photolysis rates in the presence of an arbitrary mix of cloud and aerosol layers (handles multiple layers as well).

- Enables tropospheric chemistry simulations to include directly the physical properties of scattering and absorbing particles in the column.

- The code is fast and can be applied to 3D global CTMs or CCMs with low computational cost.

→ It is a sufficiently accurate and particularly efficient scheme to apply to global models.

Unique features of Fast-JX

- Phase functions calculated using Mie theory (except for ice-clouds).
- Optimization of the phase function expansion (8 terms).
- Radiative transfer equation is solved using the finite-difference method. Additional levels are inserted for thick clouds.
- Optimization of the integration over wavelength (18 bins, from 177 to 850 nm).
- JPL and IUPAC cross-sections for various temperatures reapportioned onto the scheme's wavelength bins.

Modelling photolysis rate constants: σ & φ

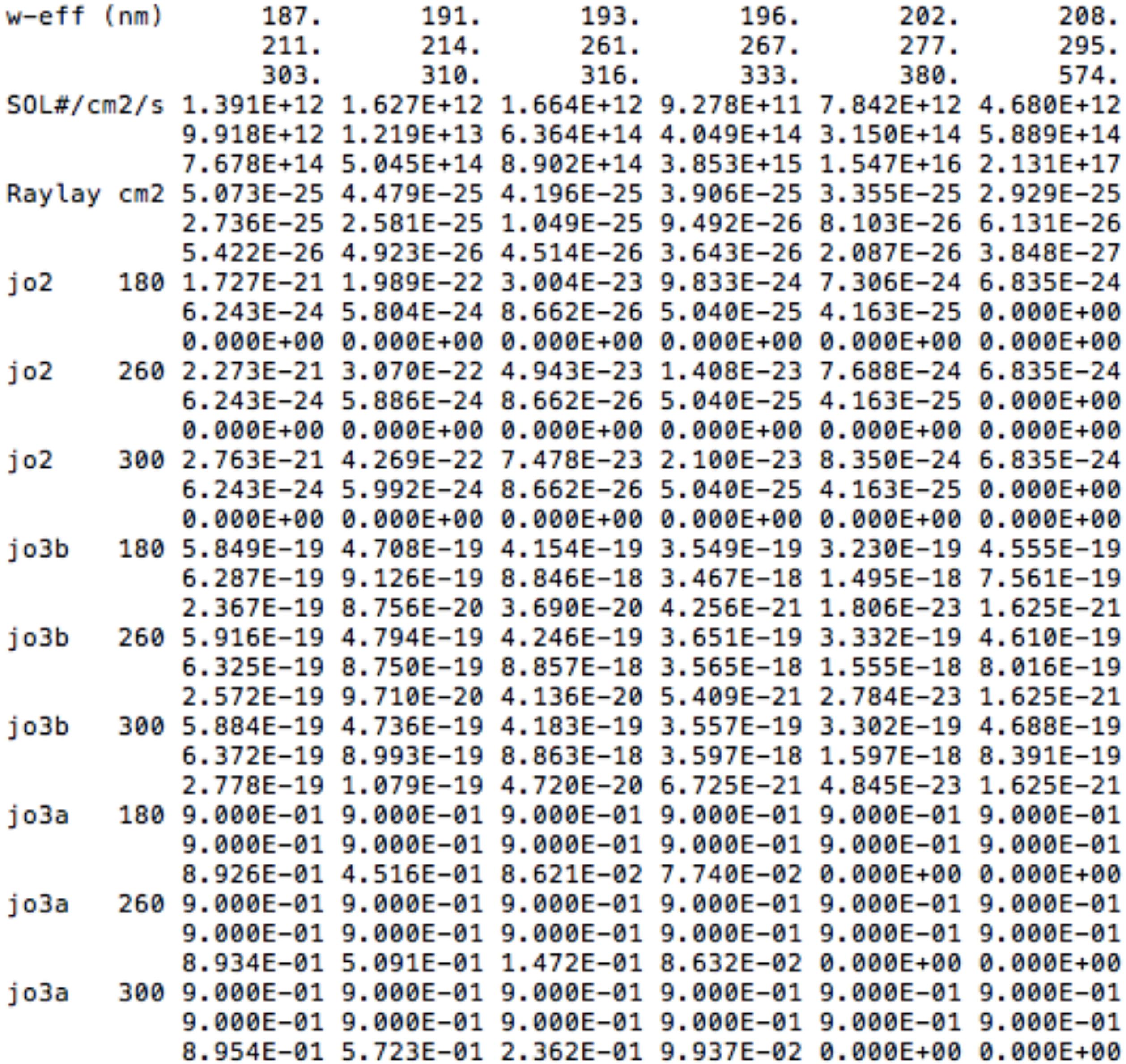
$$J_A = \int \sigma_A(\lambda)\, \varphi_A(\lambda)\, F(\lambda) d\lambda$$

- The x-sections (σ) and quantum yields (φ) for different constituents have been measured in the lab for different wavelengths, temperatures, and sometimes pressures (JPL & IUPAC reports).

- Tabulated values are then typically used in atmospheric models (e.g. see FJX_spec_Nov11.dat for UKCA).

- Real-time, simulated temperatures at different points in space and time can modify σ and φ.

In UKCA, cross sections and quantum yields are tabulated in file FJX_spec_Nov11.dat (below, its top part is shown)



```
w-eff (nm)      187.       191.       193.       196.       202.       208.
                211.       214.       261.       267.       277.       295.
                303.       310.       316.       333.       380.       574.
SOL#/cm2/s 1.391E+12 1.627E+12 1.664E+12 9.278E+11 7.842E+12 4.680E+12
           9.918E+12 1.219E+13 6.364E+14 4.049E+14 3.150E+14 5.889E+14
           7.678E+14 5.045E+14 8.902E+14 3.853E+15 1.547E+16 2.131E+17
Raylay cm2 5.073E-25 4.479E-25 4.196E-25 3.906E-25 3.355E-25 2.929E-25
           2.736E-25 2.581E-25 1.049E-25 9.492E-26 8.103E-26 6.131E-26
           5.422E-26 4.923E-26 4.514E-26 3.643E-26 2.087E-26 3.848E-27
jo2    180 1.727E-21 1.989E-22 3.004E-23 9.833E-24 7.306E-24 6.835E-24
           6.243E-24 5.804E-24 8.662E-26 5.040E-25 4.163E-25 0.000E+00
           0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
jo2    260 2.273E-21 3.070E-22 4.943E-23 1.408E-23 7.688E-24 6.835E-24
           6.243E-24 5.886E-24 8.662E-26 5.040E-25 4.163E-25 0.000E+00
           0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
jo2    300 2.763E-21 4.269E-22 7.478E-23 2.100E-23 8.350E-24 6.835E-24
           6.243E-24 5.992E-24 8.662E-26 5.040E-25 4.163E-25 0.000E+00
           0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
jo3b   180 5.849E-19 4.708E-19 4.154E-19 3.549E-19 3.230E-19 4.555E-19
           6.287E-19 9.126E-19 8.846E-18 3.467E-18 1.495E-18 7.561E-19
           2.367E-19 8.756E-20 3.690E-20 4.256E-21 1.806E-23 1.625E-21
jo3b   260 5.916E-19 4.794E-19 4.246E-19 3.651E-19 3.332E-19 4.610E-19
           6.325E-19 8.750E-19 8.857E-18 3.565E-18 1.555E-18 8.016E-19
           2.572E-19 9.710E-20 4.136E-20 5.409E-21 2.784E-23 1.625E-21
jo3b   300 5.884E-19 4.736E-19 4.183E-19 3.557E-19 3.302E-19 4.688E-19
           6.372E-19 8.993E-19 8.863E-18 3.597E-18 1.597E-18 8.391E-19
           2.778E-19 1.079E-19 4.720E-20 6.725E-21 4.845E-23 1.625E-21
jo3a   180 9.000E-01 9.000E-01 9.000E-01 9.000E-01 9.000E-01 9.000E-01
           9.000E-01 9.000E-01 9.000E-01 9.000E-01 9.000E-01 9.000E-01
           8.926E-01 4.516E-01 8.621E-02 7.740E-02 0.000E+00 0.000E+00
jo3a   260 9.000E-01 9.000E-01 9.000E-01 9.000E-01 9.000E-01 9.000E-01
           9.000E-01 9.000E-01 9.000E-01 9.000E-01 9.000E-01 9.000E-01
           8.934E-01 5.091E-01 1.472E-01 8.632E-02 0.000E+00 0.000E+00
jo3a   300 9.000E-01 9.000E-01 9.000E-01 9.000E-01 9.000E-01 9.000E-01
           9.000E-01 9.000E-01 9.000E-01 9.000E-01 9.000E-01 9.000E-01
           8.954E-01 5.723E-01 2.362E-01 9.937E-02 0.000E+00 0.000E+00
```

Modelling photolysis rate constants: *F*

$$J_A = \int \sigma_A(\lambda)\, \varphi_A(\lambda)\, F(\lambda) d\lambda$$

- Typically, actinic fluxes are simulated online for every point in space and time, accounting for modelled clouds, surface albedo, gas (e.g. O_2, O_3, NO_2), and aerosol absorption, and for TOA spectral fluxes and the solar zenith angle.

- There are two terms that need to be summed in order to calculate the actinic flux:

a) the direct solar flux, obtained from the Beer-Lambert law:

$$I_{DIR}(z,\lambda) = I_{TOA}(\lambda) * exp(-\tau(z,\lambda))$$

b) the 4π integrated mean specific intensity originating from all directions after undergoing multiple scattering by surrounding particles.

Modelling photolysis rate constants: *F (cont.)*

$$J_A = \int \sigma_A(\lambda)\, \varphi_A(\lambda)\, F(\lambda) d\lambda$$

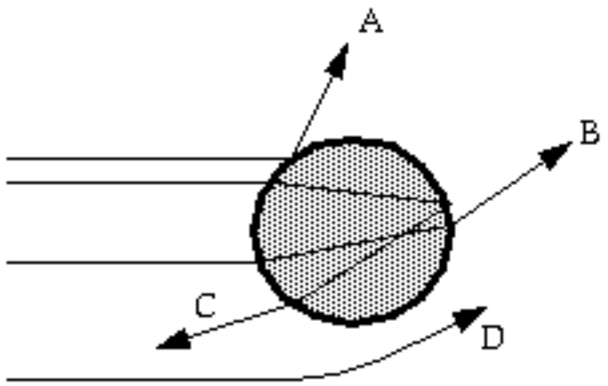
- Discrimination between the role of scattering and absorption is given by the single scattering albedo (ω), the ratio of scattering/total extinction.
- The scattering phase function (P) gives the angular distribution of light around a particle following scattering.
- In the Rayleigh scattering regime (small particles), forward- and backward-scattered radiation are symmetric. For larger particles, the forward peak becomes stronger.
- P & ω of different aerosol/cloud types are pre-calculated for five wavelengths using an offline code that performs calculations based on Mie theory for particle types with given refractive indices and sizes (see FJX_scat.dat for UKCA).

Aerosol & cloud radiative effects

Absorption

- Black carbon: the main aerosol absorber in all solar wavelengths (then re-emits thermal). Also some absorption by dust and a bit by organic carbon.
- Dust & sea-salt absorb substantially in thermal wavelengths (3,000-15,000 nm).
- Clouds absorb radiation, but how much is absorbed depends on the cloud type.

Scattering (only for solar)



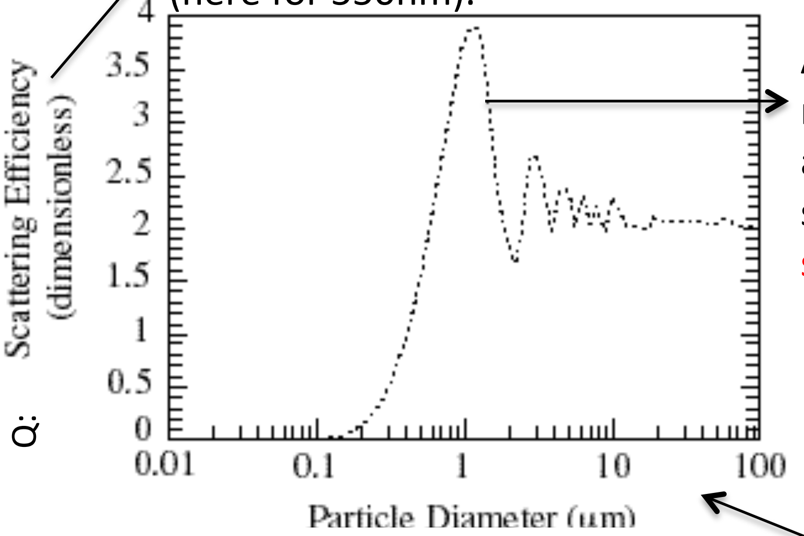
A: Reflection B: Refraction

C: Refraction & internal reflection

D: Diffraction

(Their combination results in scattering)

Fraction of light scattered (here for 550nm).



Accumulation mode aerosols are the best scatterers (e.g. sulphate etc).

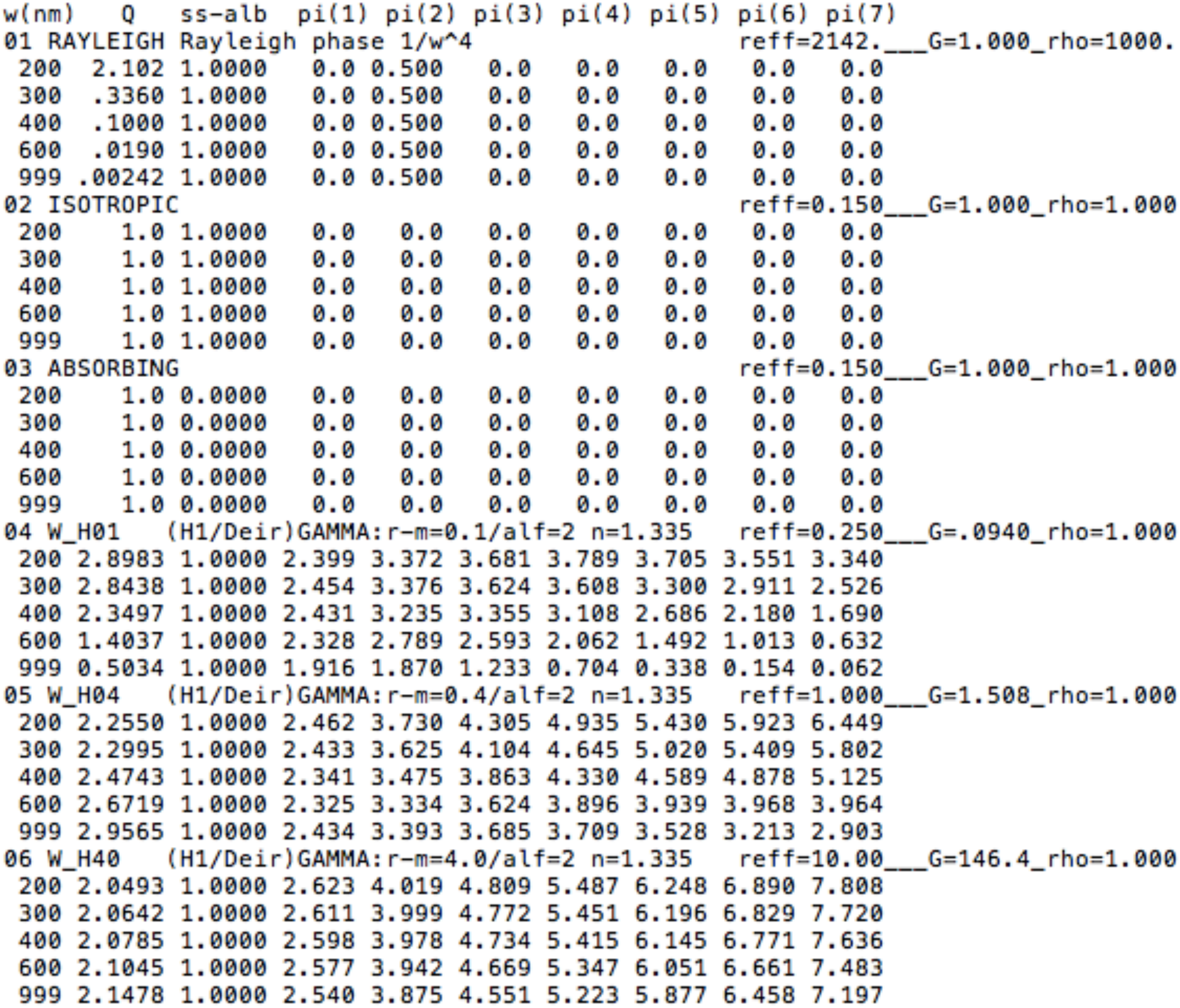
Jacobson (1998)

$$\tau_\lambda = \int_0^z k_\lambda(z)\rho(z)dz = \int_0^z \alpha_\lambda(z)dz$$

$$\alpha_\lambda = n\pi r^2 Q_\lambda$$

$$\tau_\lambda = \int_0^z n(z)\pi r^2 Q_\lambda(z)dz = \int_0^z n(z)\sigma_\lambda(z)dz$$

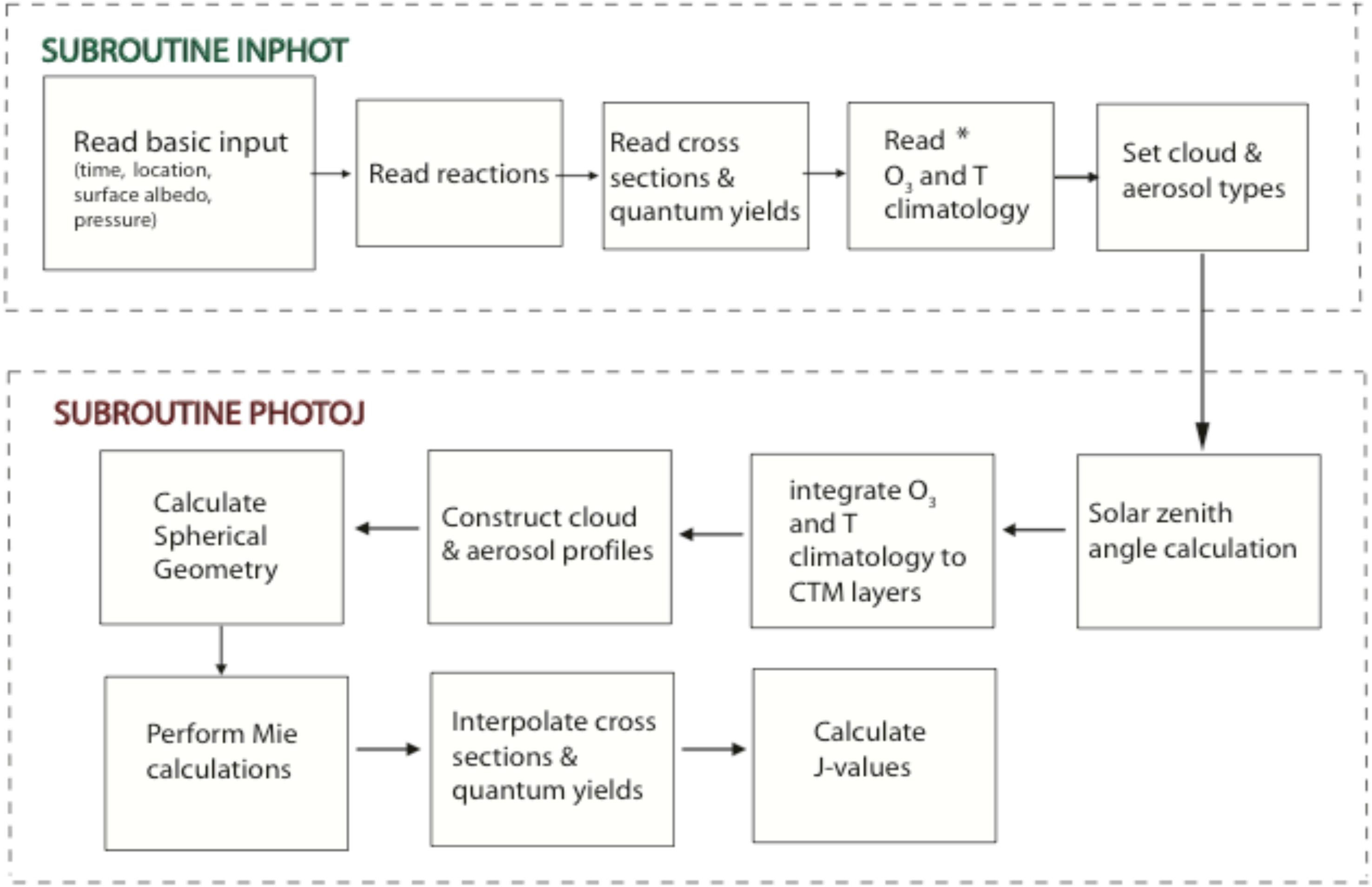
Aerosol and cloud optical properties are tabulated in file **FJX_scat.dat** (below, its top part is shown)



```
w(nm)   Q   ss-alb  pi(1) pi(2) pi(3) pi(4) pi(5) pi(6) pi(7)
01 RAYLEIGH Rayleigh phase 1/w^4                  reff=2142.___G=1.000_rho=1000.
 200  2.102 1.0000   0.0 0.500   0.0   0.0   0.0   0.0   0.0
 300  .3360 1.0000   0.0 0.500   0.0   0.0   0.0   0.0   0.0
 400  .1000 1.0000   0.0 0.500   0.0   0.0   0.0   0.0   0.0
 600  .0190 1.0000   0.0 0.500   0.0   0.0   0.0   0.0   0.0
 999 .00242 1.0000   0.0 0.500   0.0   0.0   0.0   0.0   0.0
02 ISOTROPIC                                      reff=0.150___G=1.000_rho=1.000
 200    1.0 1.0000   0.0   0.0   0.0   0.0   0.0   0.0   0.0
 300    1.0 1.0000   0.0   0.0   0.0   0.0   0.0   0.0   0.0
 400    1.0 1.0000   0.0   0.0   0.0   0.0   0.0   0.0   0.0
 600    1.0 1.0000   0.0   0.0   0.0   0.0   0.0   0.0   0.0
 999    1.0 1.0000   0.0   0.0   0.0   0.0   0.0   0.0   0.0
03 ABSORBING                                      reff=0.150___G=1.000_rho=1.000
 200    1.0 0.0000   0.0   0.0   0.0   0.0   0.0   0.0   0.0
 300    1.0 0.0000   0.0   0.0   0.0   0.0   0.0   0.0   0.0
 400    1.0 0.0000   0.0   0.0   0.0   0.0   0.0   0.0   0.0
 600    1.0 0.0000   0.0   0.0   0.0   0.0   0.0   0.0   0.0
 999    1.0 0.0000   0.0   0.0   0.0   0.0   0.0   0.0   0.0
04 W_H01   (H1/Deir)GAMMA:r-m=0.1/alf=2 n=1.335   reff=0.250___G=.0940_rho=1.000
 200 2.8983 1.0000 2.399 3.372 3.681 3.789 3.705 3.551 3.340
 300 2.8438 1.0000 2.454 3.376 3.624 3.608 3.300 2.911 2.526
 400 2.3497 1.0000 2.431 3.235 3.355 3.108 2.686 2.180 1.690
 600 1.4037 1.0000 2.328 2.789 2.593 2.062 1.492 1.013 0.632
 999 0.5034 1.0000 1.916 1.870 1.233 0.704 0.338 0.154 0.062
05 W_H04   (H1/Deir)GAMMA:r-m=0.4/alf=2 n=1.335   reff=1.000___G=1.508_rho=1.000
 200 2.2550 1.0000 2.462 3.730 4.305 4.935 5.430 5.923 6.449
 300 2.2995 1.0000 2.433 3.625 4.104 4.645 5.020 5.409 5.802
 400 2.4743 1.0000 2.341 3.475 3.863 4.330 4.589 4.878 5.125
 600 2.6719 1.0000 2.325 3.334 3.624 3.896 3.939 3.968 3.964
 999 2.9565 1.0000 2.434 3.393 3.685 3.709 3.528 3.213 2.903
06 W_H40   (H1/Deir)GAMMA:r-m=4.0/alf=2 n=1.335   reff=10.00___G=146.4_rho=1.000
 200 2.0493 1.0000 2.623 4.019 4.809 5.487 6.248 6.890 7.808
 300 2.0642 1.0000 2.611 3.999 4.772 5.451 6.196 6.829 7.720
 400 2.0785 1.0000 2.598 3.978 4.734 5.415 6.145 6.771 7.636
 600 2.1045 1.0000 2.577 3.942 4.669 5.347 6.051 6.661 7.483
 999 2.1478 1.0000 2.540 3.875 4.551 5.223 5.877 6.458 7.197
```

Flowchart of standalone version of the Fast-J scheme

(that presented in Wild et al. (2000) - somewhat earlier than the Fast-JX version used in UKCA)



SUBROUTINE INPHOT

Read basic input (time, location, surface albedo, pressure)

Read reactions

Read cross sections & quantum yields

Read * O_3 and T climatology

Set cloud & aerosol types

SUBROUTINE PHOTOJ

Solar zenith angle calculation

integrate O_3 and T climatology to CTM layers

Construct cloud & aerosol profiles

Calculate Spherical Geometry

Perform Mie calculations

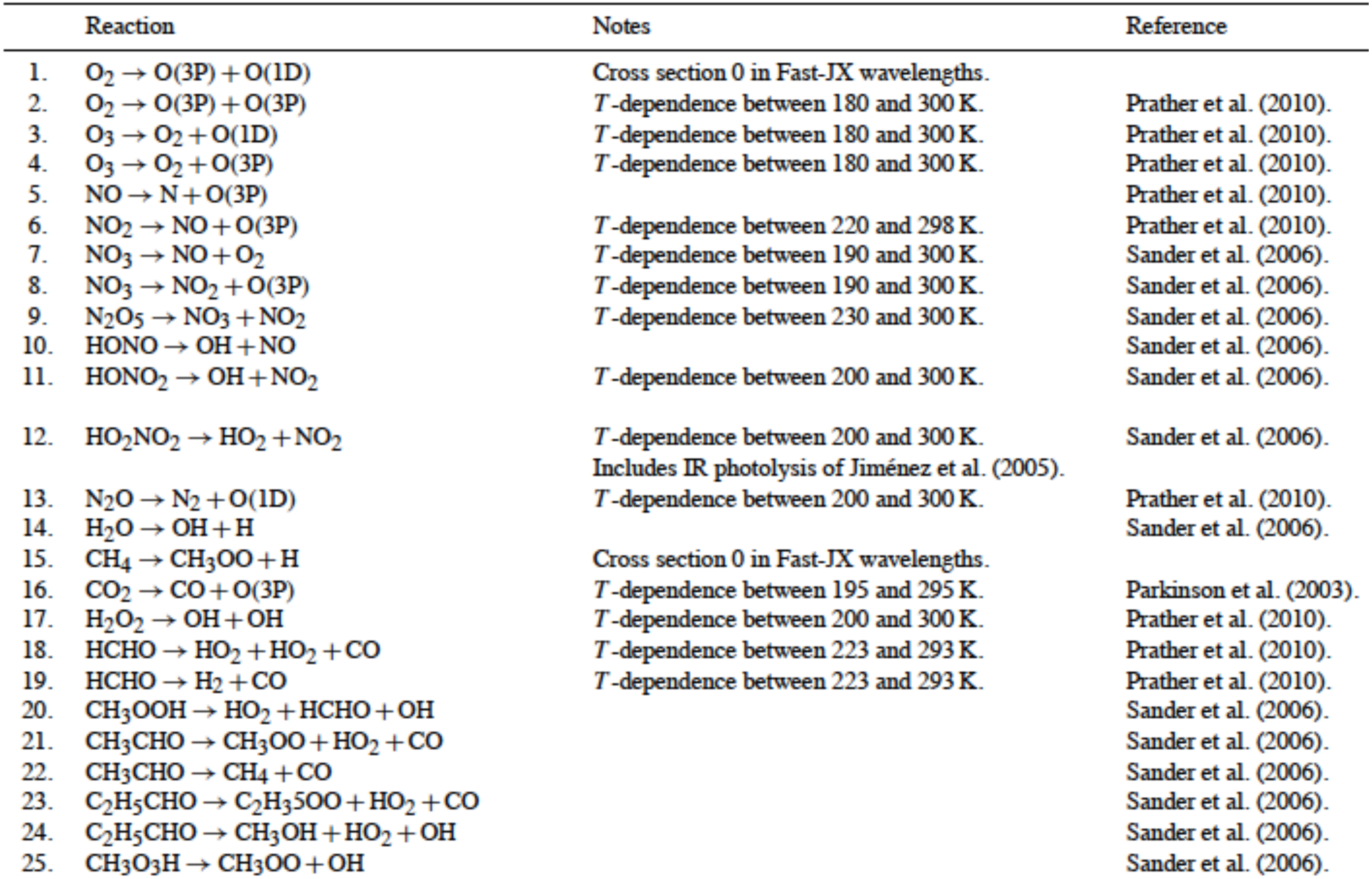
Interpolate cross sections & quantum yields

Calculate J-values

Voulgarakis et al. [2009a], GMD

Photolysis reactions included in the UKCA implementation of Fast-JX

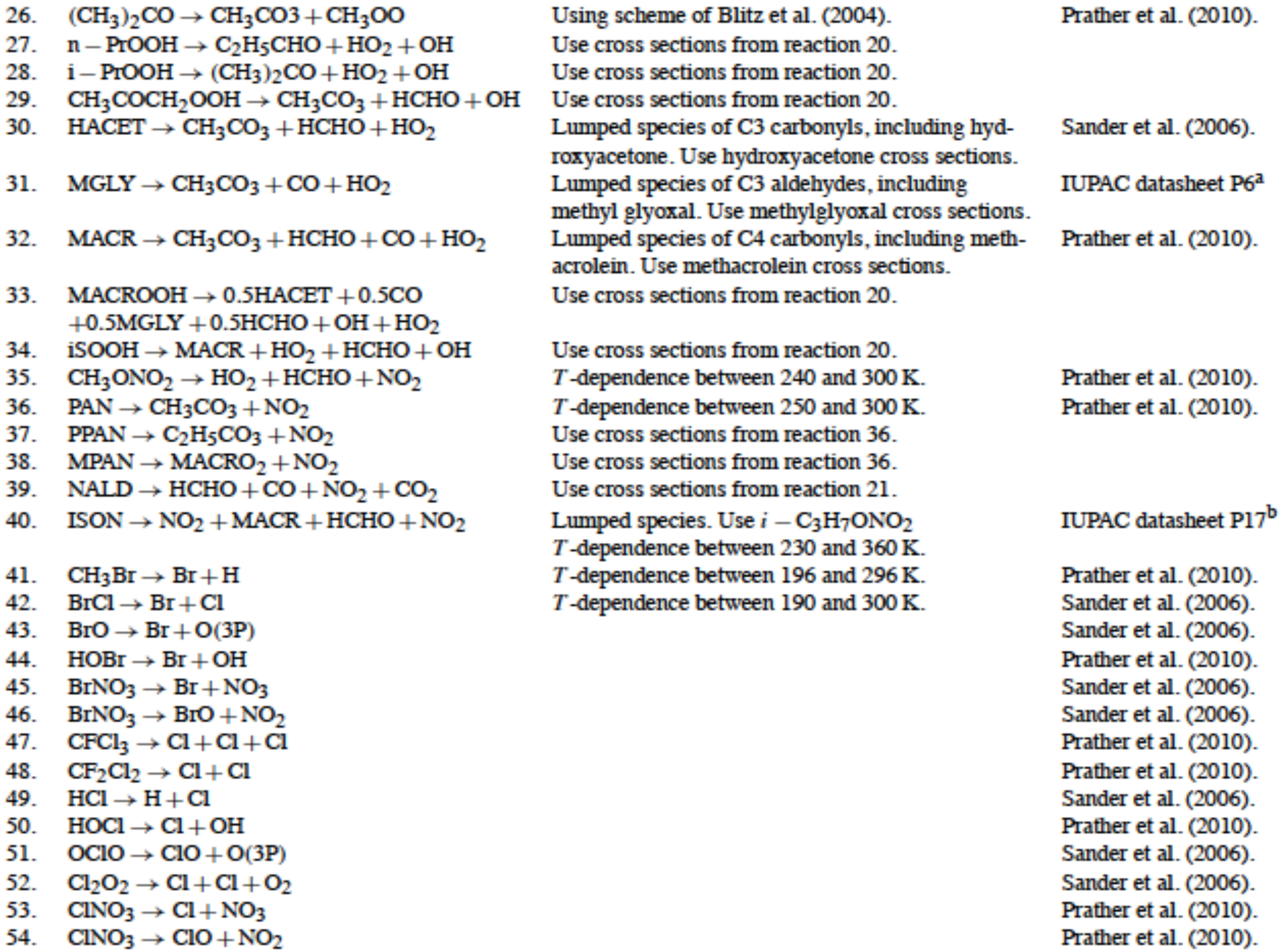
Telford et al. [2012], GMD



	Reaction	Notes	Reference
1.	$O_2 \rightarrow O(3P) + O(1D)$	Cross section 0 in Fast-JX wavelengths.	
2.	$O_2 \rightarrow O(3P) + O(3P)$	T-dependence between 180 and 300 K.	Prather et al. (2010).
3.	$O_3 \rightarrow O_2 + O(1D)$	T-dependence between 180 and 300 K.	Prather et al. (2010).
4.	$O_3 \rightarrow O_2 + O(3P)$	T-dependence between 180 and 300 K.	Prather et al. (2010).
5.	$NO \rightarrow N + O(3P)$		Prather et al. (2010).
6.	$NO_2 \rightarrow NO + O(3P)$	T-dependence between 220 and 298 K.	Prather et al. (2010).
7.	$NO_3 \rightarrow NO + O_2$	T-dependence between 190 and 300 K.	Sander et al. (2006).
8.	$NO_3 \rightarrow NO_2 + O(3P)$	T-dependence between 190 and 300 K.	Sander et al. (2006).
9.	$N_2O_5 \rightarrow NO_3 + NO_2$	T-dependence between 230 and 300 K.	Sander et al. (2006).
10.	$HONO \rightarrow OH + NO$		Sander et al. (2006).
11.	$HONO_2 \rightarrow OH + NO_2$	T-dependence between 200 and 300 K.	Sander et al. (2006).
12.	$HO_2NO_2 \rightarrow HO_2 + NO_2$	T-dependence between 200 and 300 K. Includes IR photolysis of Jiménez et al. (2005).	Sander et al. (2006).
13.	$N_2O \rightarrow N_2 + O(1D)$	T-dependence between 200 and 300 K.	Prather et al. (2010).
14.	$H_2O \rightarrow OH + H$		Sander et al. (2006).
15.	$CH_4 \rightarrow CH_3OO + H$	Cross section 0 in Fast-JX wavelengths.	
16.	$CO_2 \rightarrow CO + O(3P)$	T-dependence between 195 and 295 K.	Parkinson et al. (2003).
17.	$H_2O_2 \rightarrow OH + OH$	T-dependence between 200 and 300 K.	Prather et al. (2010).
18.	$HCHO \rightarrow HO_2 + HO_2 + CO$	T-dependence between 223 and 293 K.	Prather et al. (2010).
19.	$HCHO \rightarrow H_2 + CO$	T-dependence between 223 and 293 K.	Prather et al. (2010).
20.	$CH_3OOH \rightarrow HO_2 + HCHO + OH$		Sander et al. (2006).
21.	$CH_3CHO \rightarrow CH_3OO + HO_2 + CO$		Sander et al. (2006).
22.	$CH_3CHO \rightarrow CH_4 + CO$		Sander et al. (2006).
23.	$C_2H_5CHO \rightarrow C_2H_35OO + HO_2 + CO$		Sander et al. (2006).
24.	$C_2H_5CHO \rightarrow CH_3OH + HO_2 + OH$		Sander et al. (2006).
25.	$CH_3O_3H \rightarrow CH_3OO + OH$		Sander et al. (2006).

Photolysis reactions included in the UKCA implementation of Fast-JX (cont.)

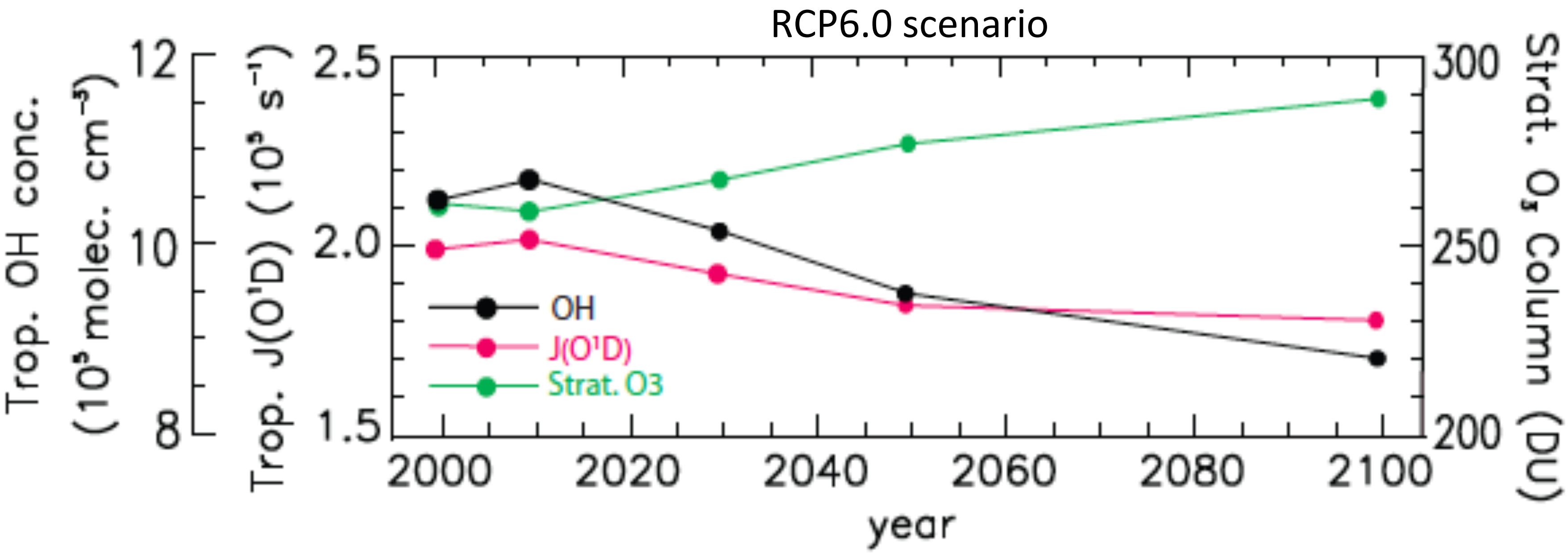
Telford et al. [2012], GMD



26.	$(CH_3)_2CO \rightarrow CH_3CO3 + CH_3OO$	Using scheme of Blitz et al. (2004).	Prather et al. (2010).
27.	$n-PrOOH \rightarrow C_2H_5CHO + HO_2 + OH$	Use cross sections from reaction 20.	
28.	$i-PrOOH \rightarrow (CH_3)_2CO + HO_2 + OH$	Use cross sections from reaction 20.	
29.	$CH_3COCH_2OOH \rightarrow CH_3CO_3 + HCHO + OH$	Use cross sections from reaction 20.	
30.	$HACET \rightarrow CH_3CO_3 + HCHO + HO_2$	Lumped species of C3 carbonyls, including hydroxyacetone. Use hydroxyacetone cross sections.	Sander et al. (2006).
31.	$MGLY \rightarrow CH_3CO_3 + CO + HO_2$	Lumped species of C3 aldehydes, including methyl glyoxal. Use methylglyoxal cross sections.	IUPAC datasheet P6[a]
32.	$MACR \rightarrow CH_3CO_3 + HCHO + CO + HO_2$	Lumped species of C4 carbonyls, including methacrolein. Use methacrolein cross sections.	Prather et al. (2010).
33.	$MACROOH \rightarrow 0.5HACET + 0.5CO + 0.5MGLY + 0.5HCHO + OH + HO_2$	Use cross sections from reaction 20.	
34.	$iSOOH \rightarrow MACR + HO_2 + HCHO + OH$	Use cross sections from reaction 20.	
35.	$CH_3ONO_2 \rightarrow HO_2 + HCHO + NO_2$	T-dependence between 240 and 300 K.	Prather et al. (2010).
36.	$PAN \rightarrow CH_3CO_3 + NO_2$	T-dependence between 250 and 300 K.	Prather et al. (2010).
37.	$PPAN \rightarrow C_2H_5CO_3 + NO_2$	Use cross sections from reaction 36.	
38.	$MPAN \rightarrow MACRO_2 + NO_2$	Use cross sections from reaction 36.	
39.	$NALD \rightarrow HCHO + CO + NO_2 + CO_2$	Use cross sections from reaction 21.	
40.	$ISON \rightarrow NO_2 + MACR + HCHO + NO_2$	Lumped species. Use $i-C_3H_7ONO_2$ T-dependence between 230 and 360 K.	IUPAC datasheet P17[b]
41.	$CH_3Br \rightarrow Br + H$	T-dependence between 196 and 296 K.	Prather et al. (2010).
42.	$BrCl \rightarrow Br + Cl$	T-dependence between 190 and 300 K.	Sander et al. (2006).
43.	$BrO \rightarrow Br + O(3P)$		Sander et al. (2006).
44.	$HOBr \rightarrow Br + OH$		Prather et al. (2010).
45.	$BrNO_3 \rightarrow Br + NO_3$		Sander et al. (2006).
46.	$BrNO_3 \rightarrow BrO + NO_2$		Sander et al. (2006).
47.	$CFCl_3 \rightarrow Cl + Cl + Cl$		Prather et al. (2010).
48.	$CF_2Cl_2 \rightarrow Cl + Cl$		Prather et al. (2010).
49.	$HCl \rightarrow H + Cl$		Sander et al. (2006).
50.	$HOCl \rightarrow Cl + OH$		Prather et al. (2010).
51.	$OClO \rightarrow ClO + O(3P)$		Sander et al. (2006).
52.	$Cl_2O_2 \rightarrow Cl + Cl + O_2$		Sander et al. (2006).
53.	$ClNO_3 \rightarrow Cl + NO_3$		Prather et al. (2010).
54.	$ClNO_3 \rightarrow ClO + NO_2$		Prather et al. (2010).

Example: Stratospheric ozone, tropospheric photolysis, and trop. OH (in GISS CCM with Fast-J2)

RCP6.0 scenario



Voulgarakis et al. (2013a), ACP

- Strat. O3 recovery ➔ less radiation in the troposphere ➔ slower photolysis (JO(^{1}D)) ➔ less OH

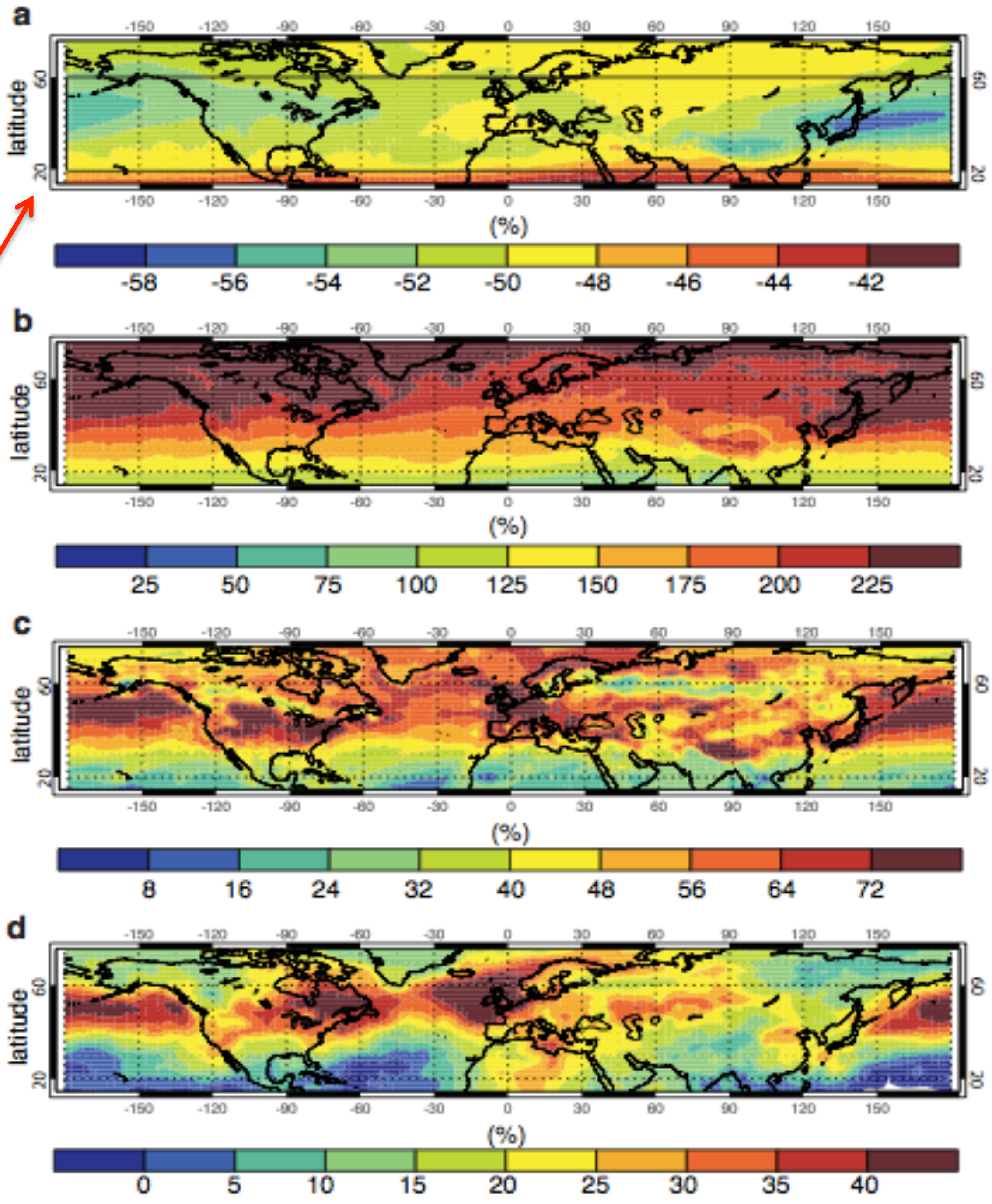
Example: **Changes in "world avoided" scenario due to photolysis** (in GISS CCM with Fast-J2)

- Ozone column

- JO(^{1}D)

- OH

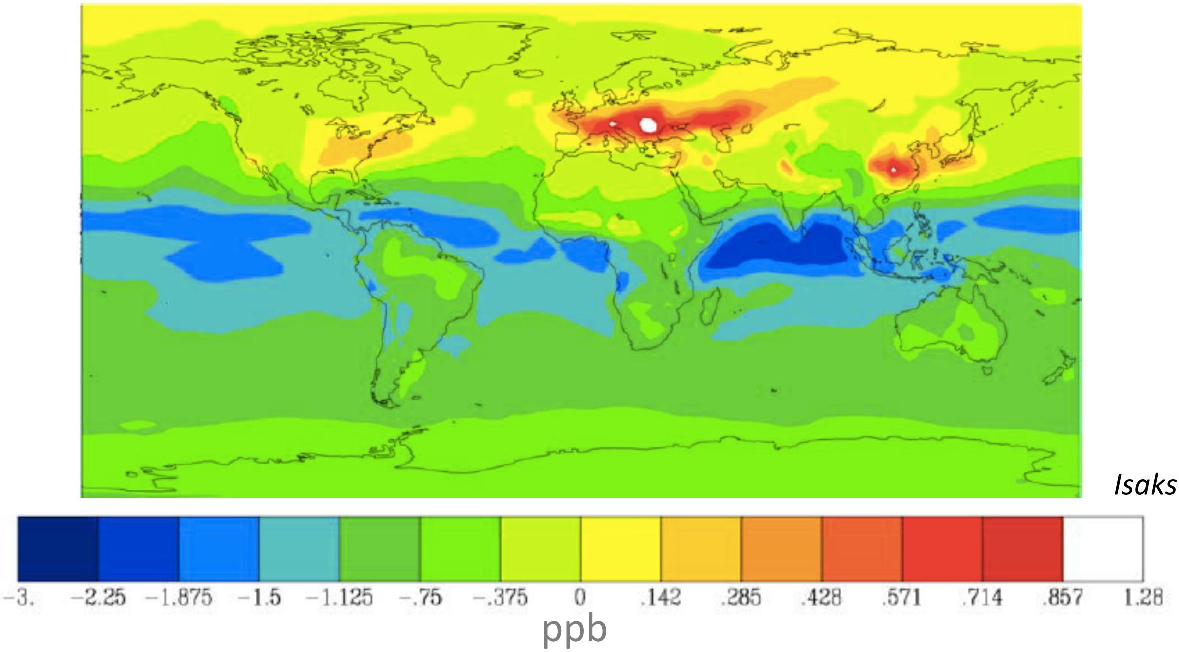
- Sulphate aerosol



Voulgarakis et al. (2013b)

Example: Changes in surface O_3 due to 10% reduction in column O_3 in January

(in OsloCTM2 with Fast-J)

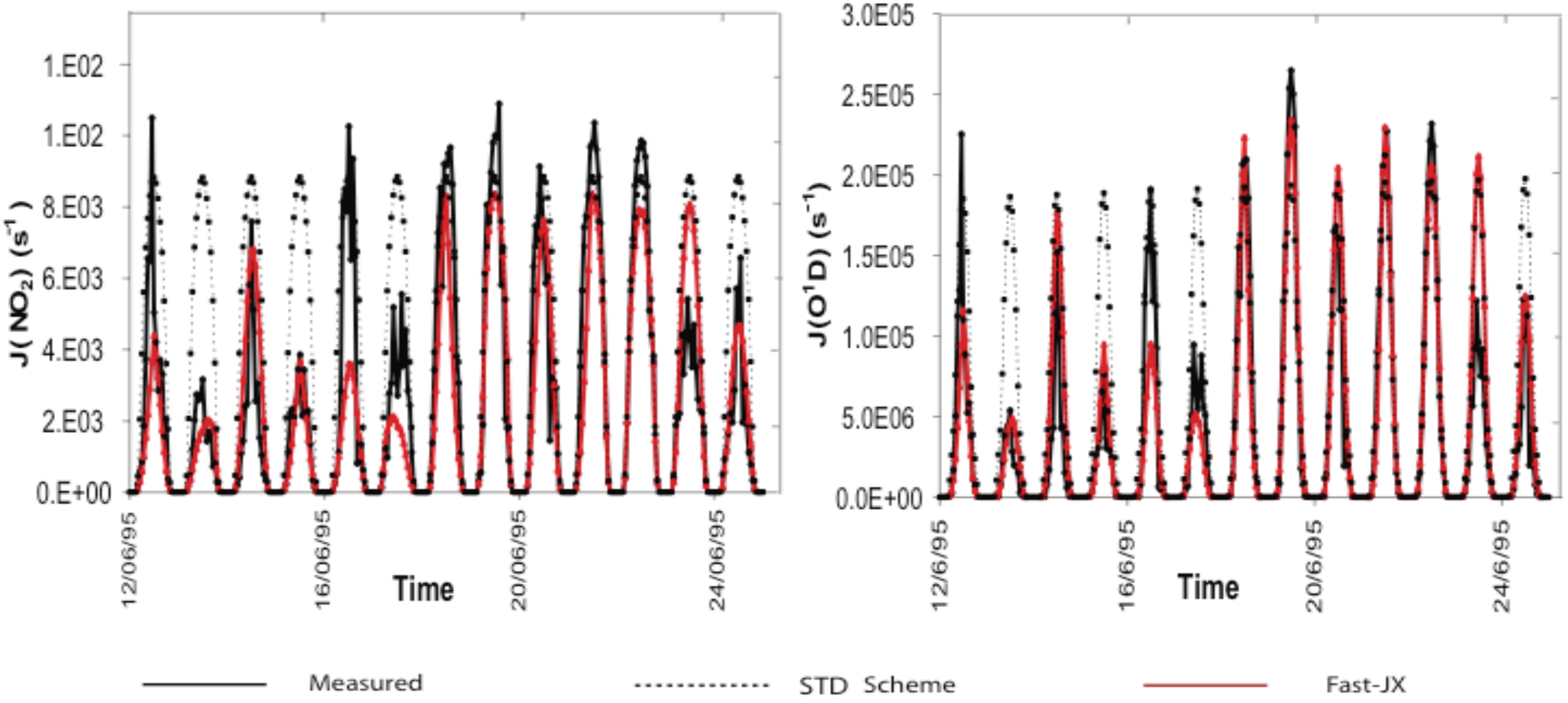


Isaksen et al. (2005), JGR

- Faster photolysis favours both O_3 production (JNO_2) and destruction ($JO(^1D)$).
- In the net, the O_3 production perturbation wins in polluted regions, and the ozone destruction wins in remote regions.

Example: Effect of clouds on photolysis

(in the *p*-TOMCAT CTM using Fast-JX)



Photolysis rates for a measurement site (Weybourne).

Black: measured.

Dotted: modeled with no cloud variations.

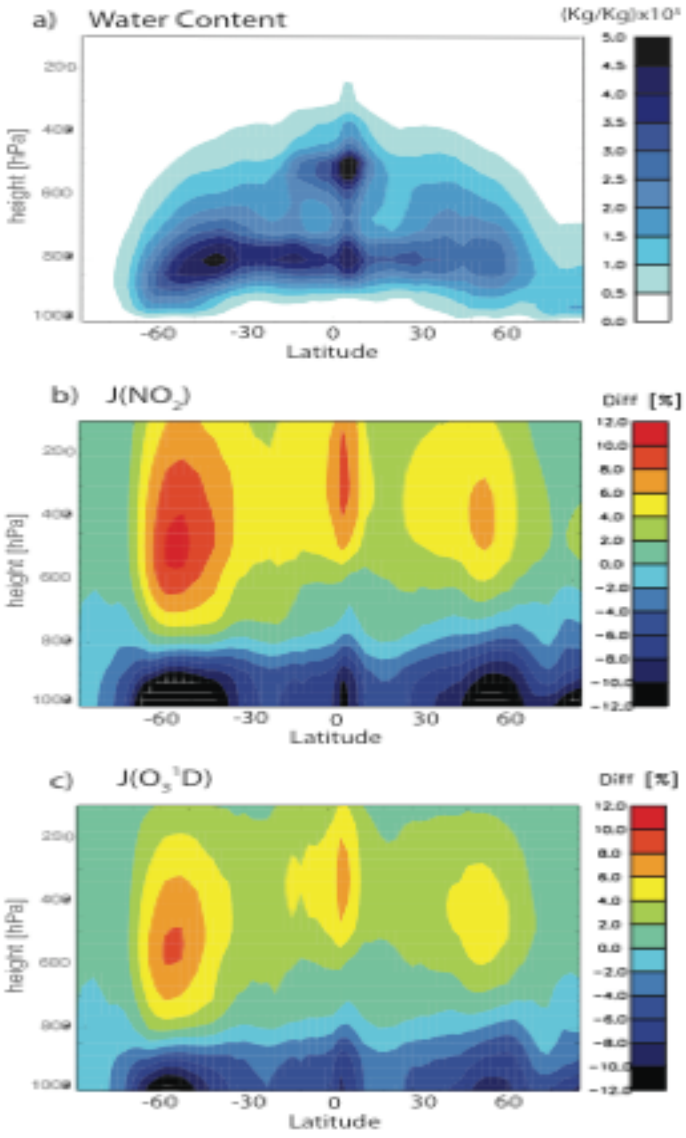
Red: modeled with cloud variations.

→ Clouds drive the day-to-day variability.

Voulgarakis et al. (2009b), GMD

Example: Effect of clouds on photolysis (cont.)

(in the *p*-TOMCAT CTM using Fast-JX)



- Distribution of cloud water content shows the multi-layered cloud structure in the tropics and the large cloud amounts in the southern midlatitudes.

- Photolysis rates are increased above clouds, decreased below them and remain intact where the main masses of clouds are.

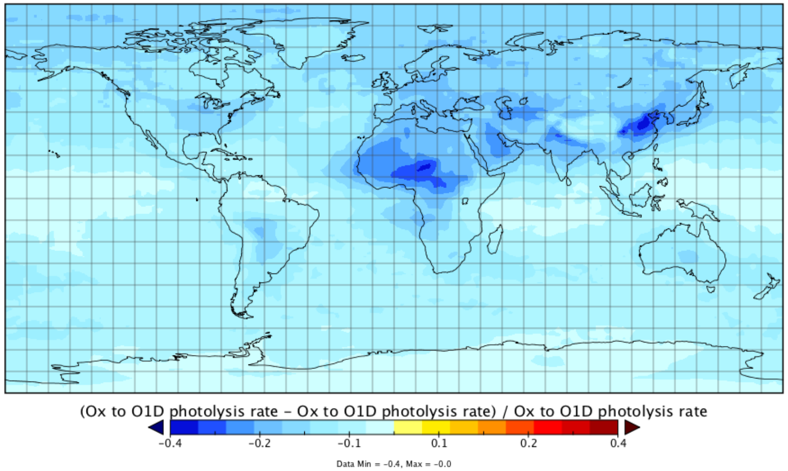
- These results are in agreement with Liu et al. (2006), who used Fast-J.

Voulgarakis et al. (2009c), ACP

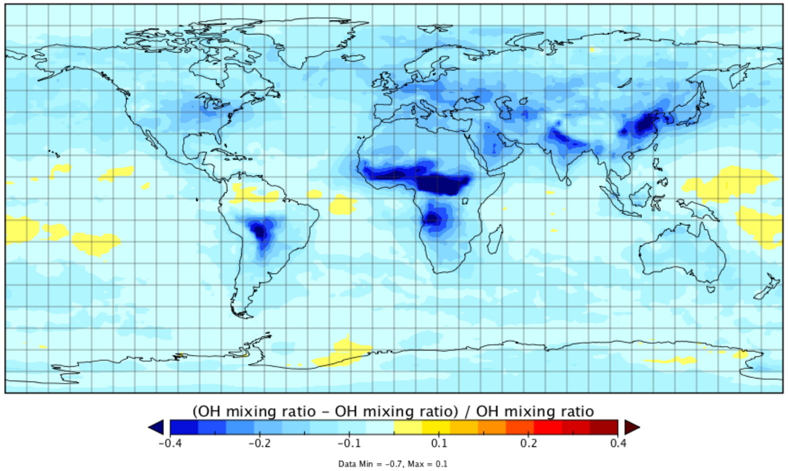
Example: **Effect of aerosols on photolysis & OH**

(in the GISS CCM with Fast-J2)

J(O^1D)



OH



- Maps show relative change of J(O^1D) and OH at the surface due to the presence of aerosols in the atmosphere.

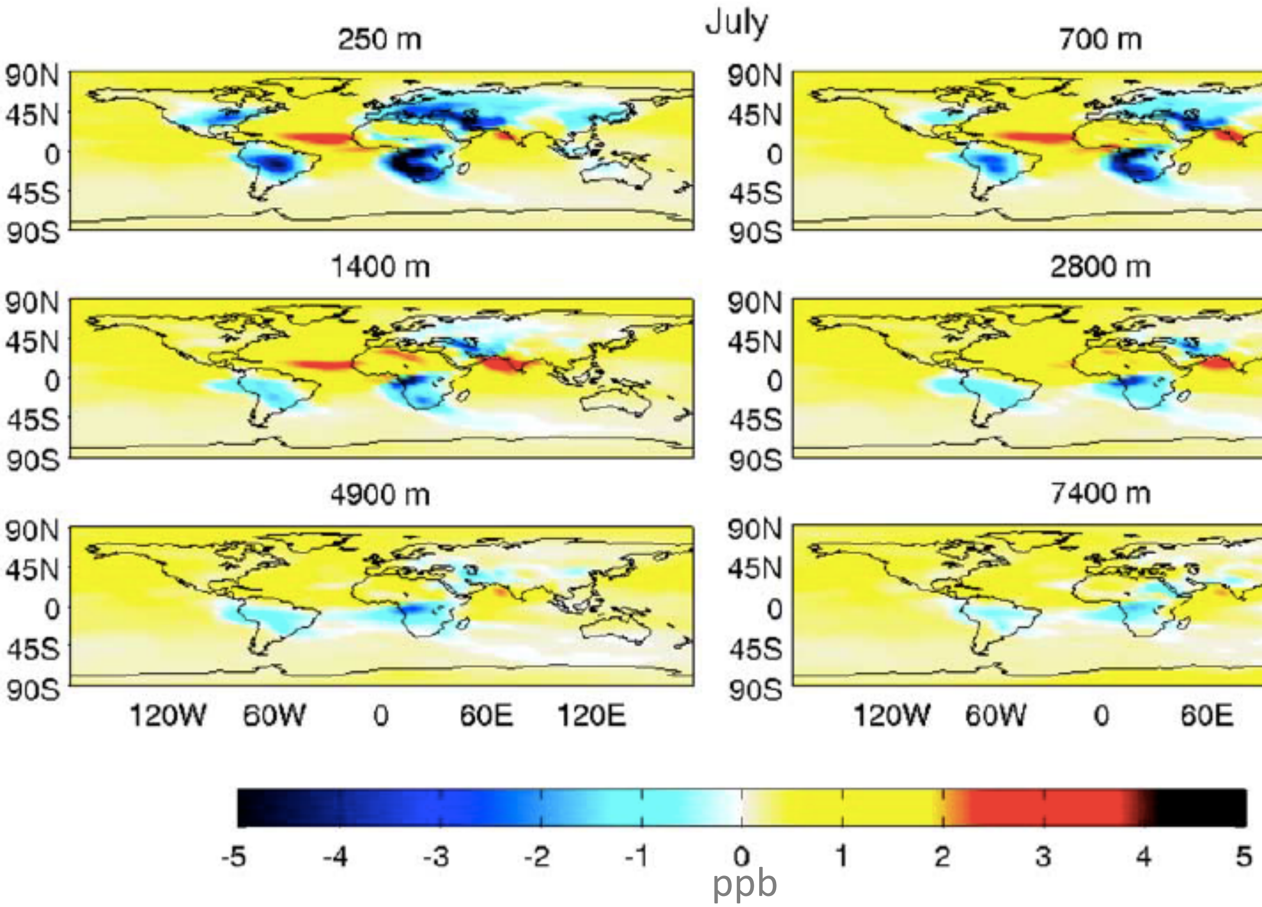
- Strong effects, especially over regions with heavy anthropogenic (East & South Asia) and biomass burning (Africa, South America) pollution.

- Possible implications for ozone, methane, CO, VOCs, aerosols over those regions.

Voulgarakis et al. (in prep.)

Example: Effect of aerosols on photolysis & O_3

(in UCI CTM with Fast-J2)



Bian et al. (2003), JGR

- Attenuation of solar radiation by aerosols leads to slower photochemical O_3 production over polluted regions, an effect that weakens with height.

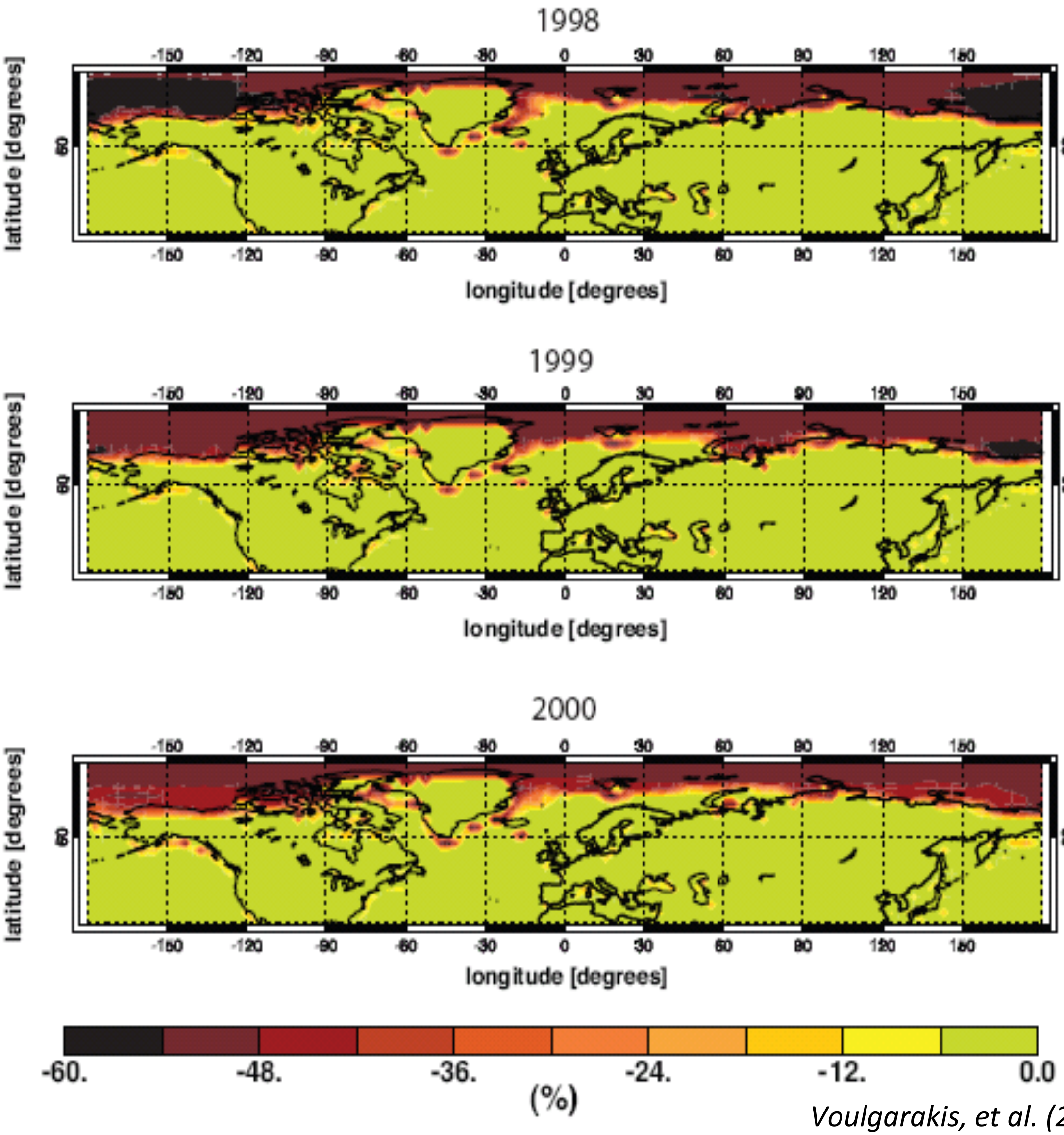
Example: Effect of surf. albedo on photolysis & OH

(in the *p*-TOMCAT CTM with Fast-JX)

- Removing Arctic sea-ice changes summer OH drastically (decreases of up to 60%).

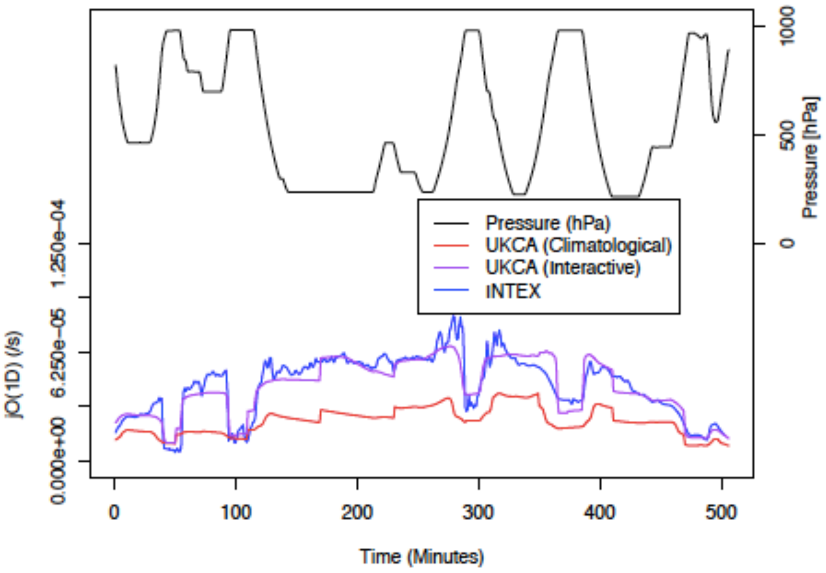
- The changes are mainly confined to polar latitudes (due to short OH lifetime).

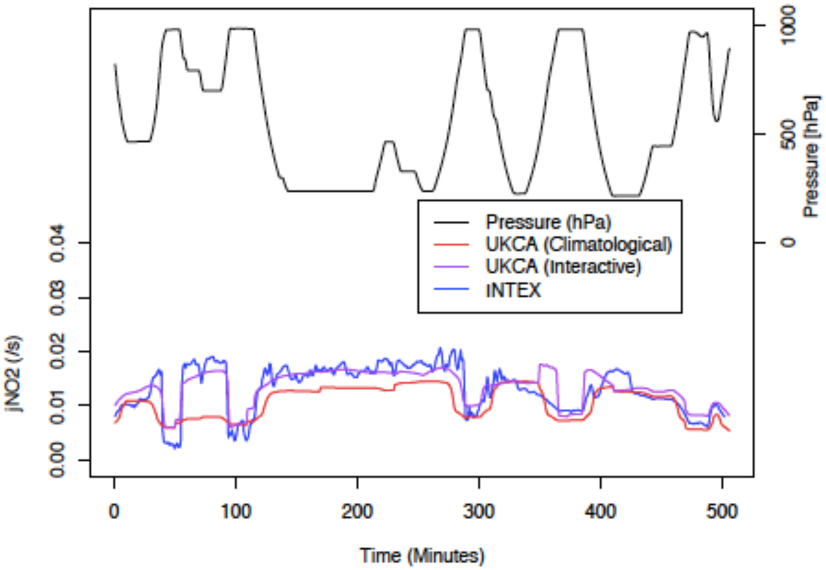
- Possibly important implications in a future, ice-free Arctic.



Voulgarakis, et al. (2009d), GRL

Evaluation of UKCA with Fast-JX (interactive) vs UKCA with offline (climatological) photolysis





Telford et al. (2012), GMD

- An example of performance of photolysis rates (JO(^{1}D) and JNO$_2$) against aircraft observations.

- Including Fast-JX (interactive) makes the simulation much more realistic.

- Offline photolysis gives a much “flatter” evolution of photolysis during the flights, as real-time clouds are not represented.

Effect of UKCA photolysis handling on OH

- Black is modelled, red is from observation-based climatology of Spivakovsky et al. (2000), and brackets are stddev within box.

- The use of the interactive photolysis scheme (Fast-JX) increases the total OH burden, which leads to decreased CO concentrations and CH_4 lifetimes (not shown).

- Found that the increases in HO_x (incl. OH) are dominated by increases in its production via $O(^1D)$+ H_2O.

Telford et al. (2012), GMD

Summary

- Photolysis is central in tropospheric and stratospheric chemistry, initiating the production of ozone and OH, the destruction of ozone, and numerous other processes.

- To model it, we use tabulated cross sections/quantum yields and aerosol optical properties, but online calculated actinic fluxes.

- Fast-JX is a state-of-the-art, accurate and efficient photolysis scheme designed for global models, currently used in UKCA.

- Important scientific insight has been provided using Fast-JX in conjunction with UKCA or other global models, when it comes to the influence of clouds, aerosols, ozone column, and surface albedo on photolysis and oxidants.

- Fast-JX will be a key tool for studying interactions as the UKCA model becomes part of the larger UKESM1 framework.