Impact of C_1-C_3 alkyl nitrate chemistry on tropospheric ozone: box and global model perspectives

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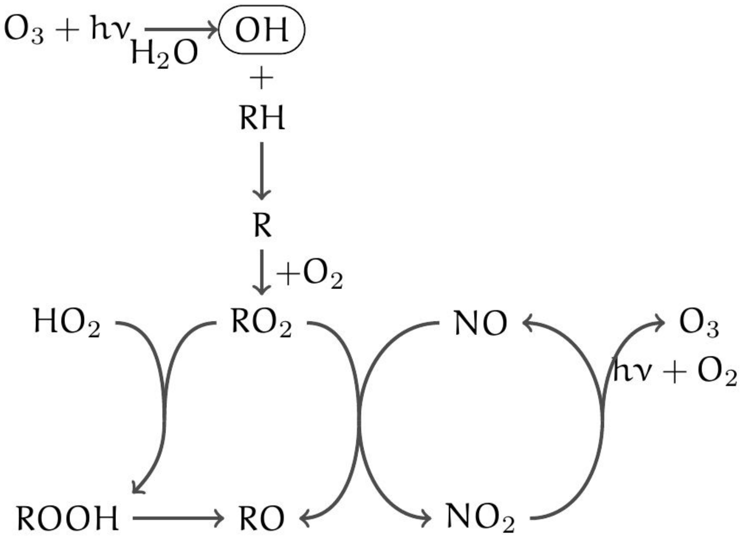
[2]National Centre for Atmospheric Science, Department of Chemistry, University of Cambridge, UK

University of East Anglia

UNIVERSITY OF CAMBRIDGE

Photography not allowed

Introduction



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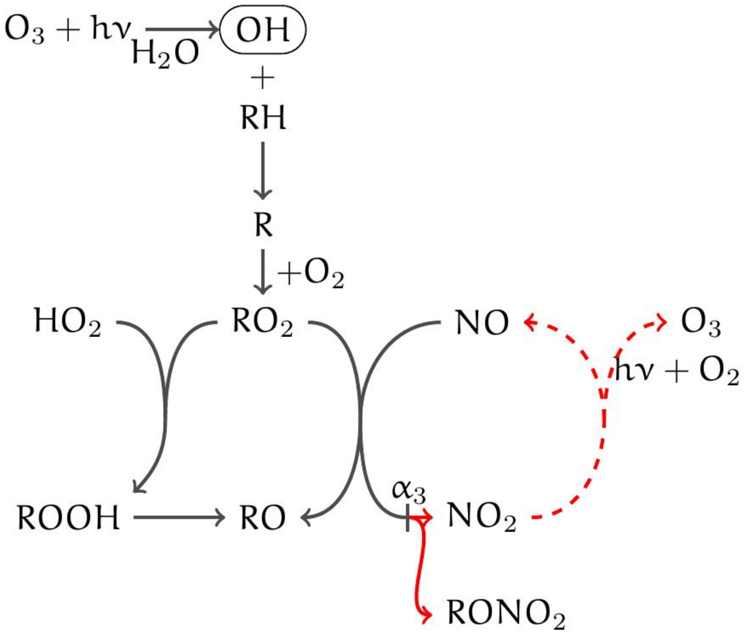

alkyl nitrates

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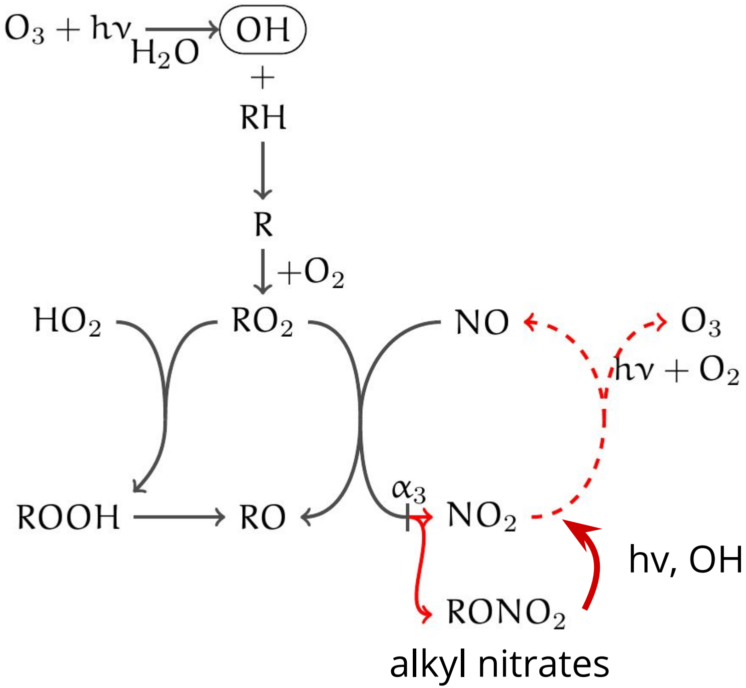

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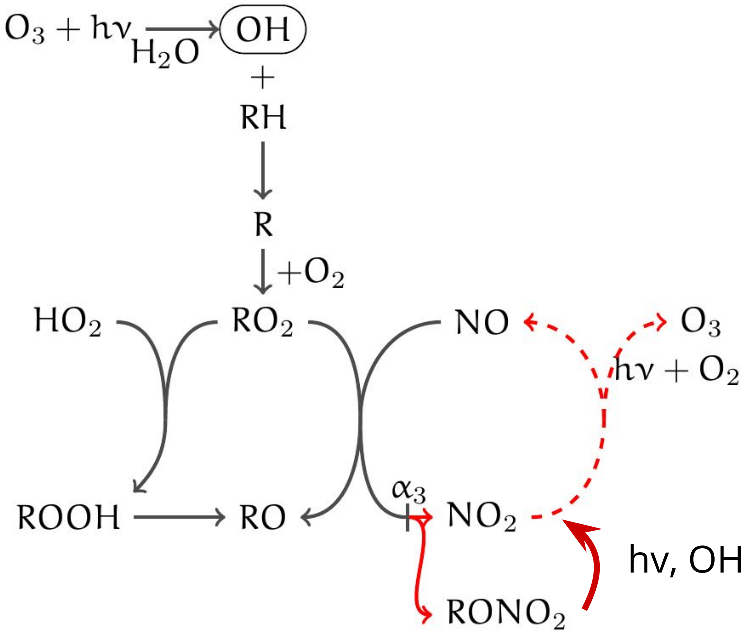
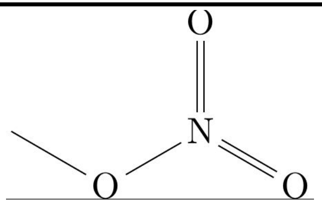
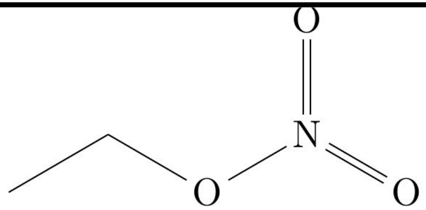


CH_4



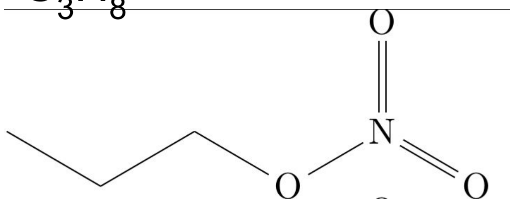
methyl nitrate ($MeONO_2$)

C_2H_6

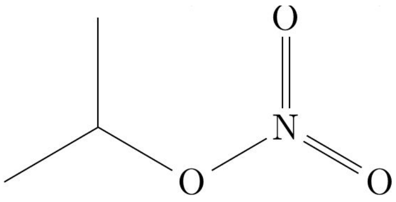


ethyl nitrate ($EtONO_2$)

C_3H_8



n-propyl nitrate ($nPrONO_2$)



iso-propyl nitrate ($iPrONO_2$)

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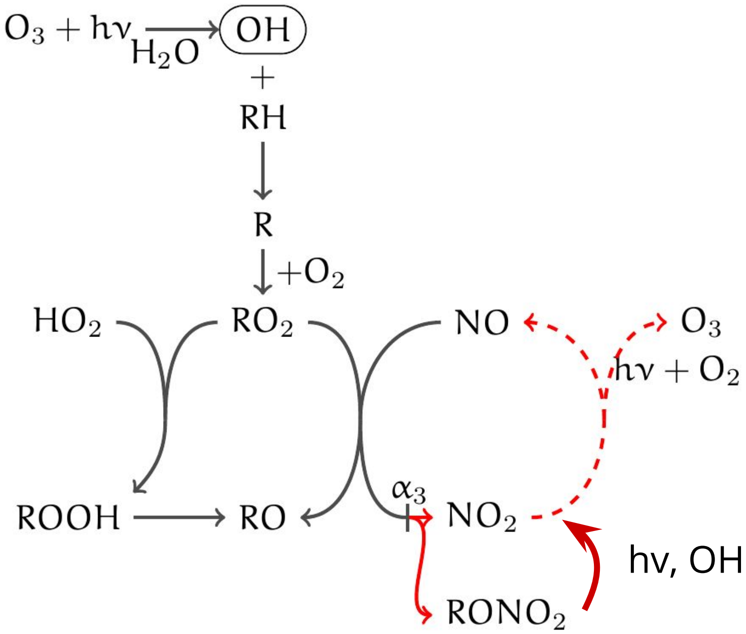

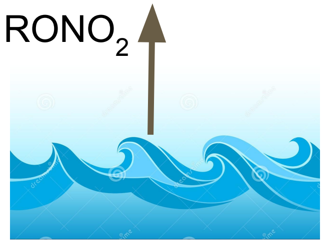

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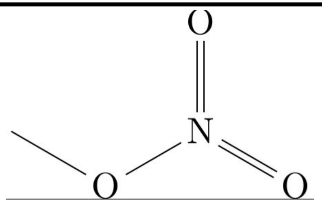

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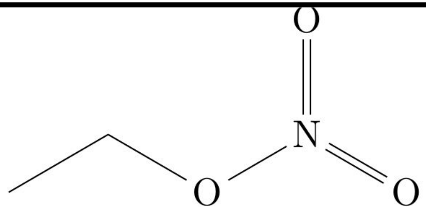

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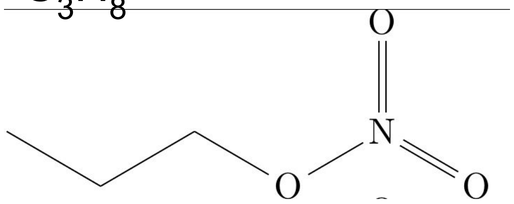

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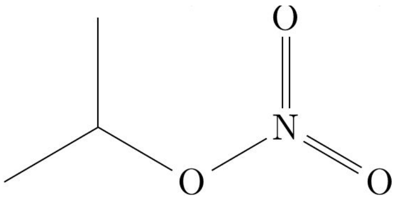

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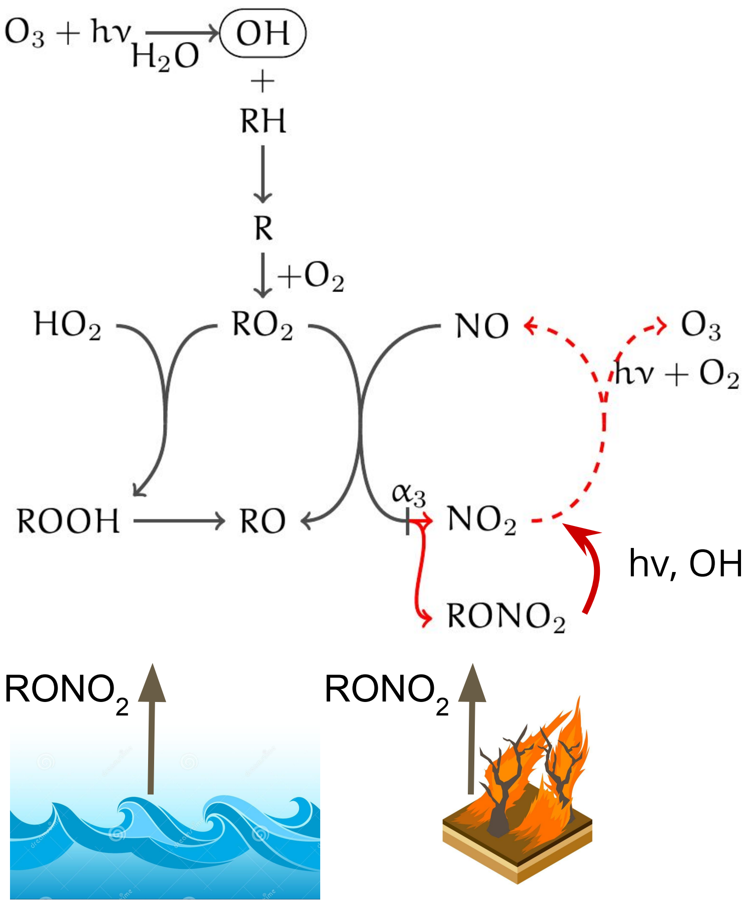

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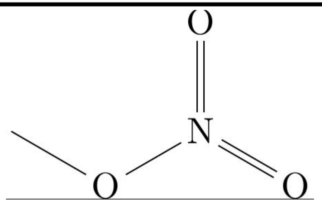

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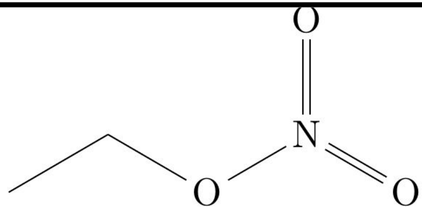

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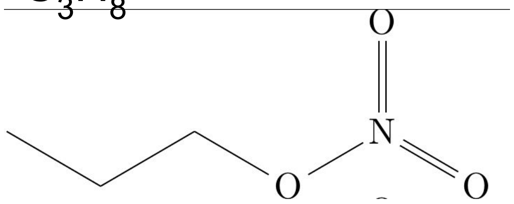

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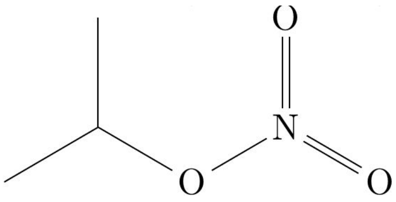

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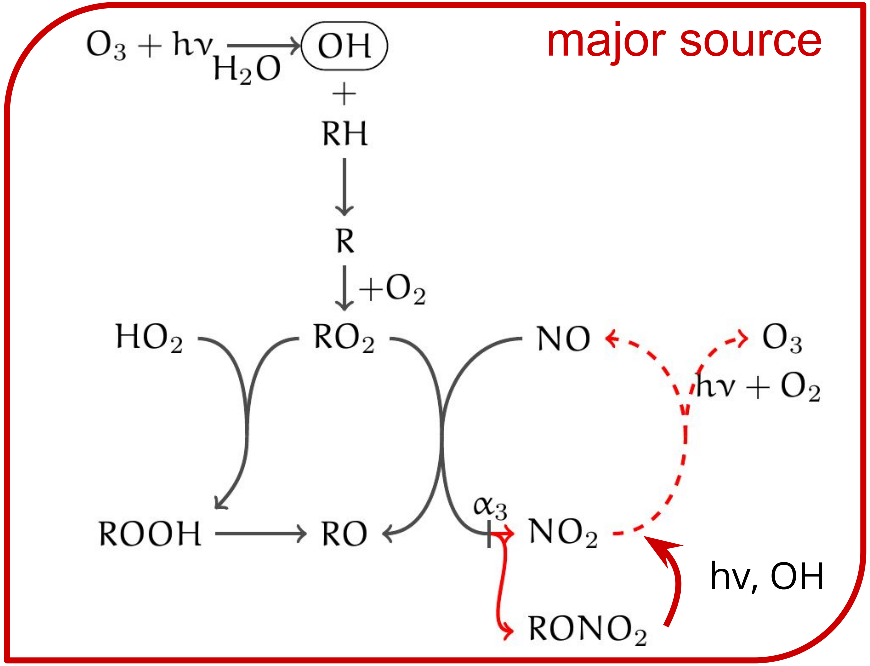

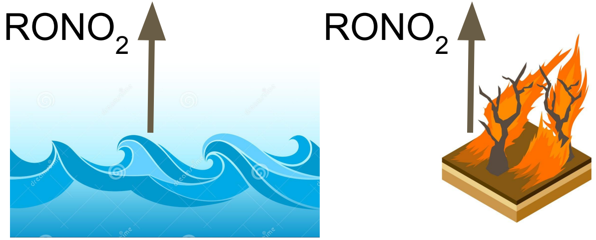

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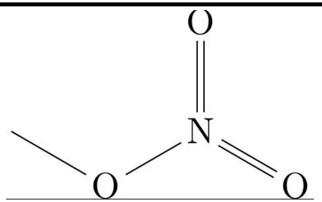

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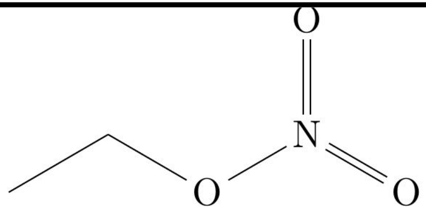

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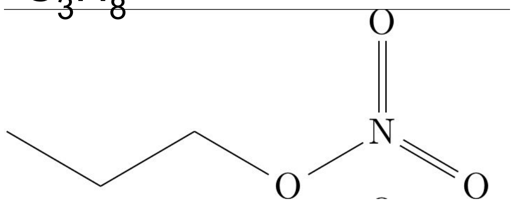

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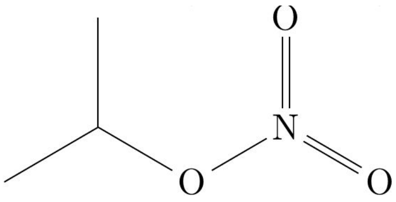
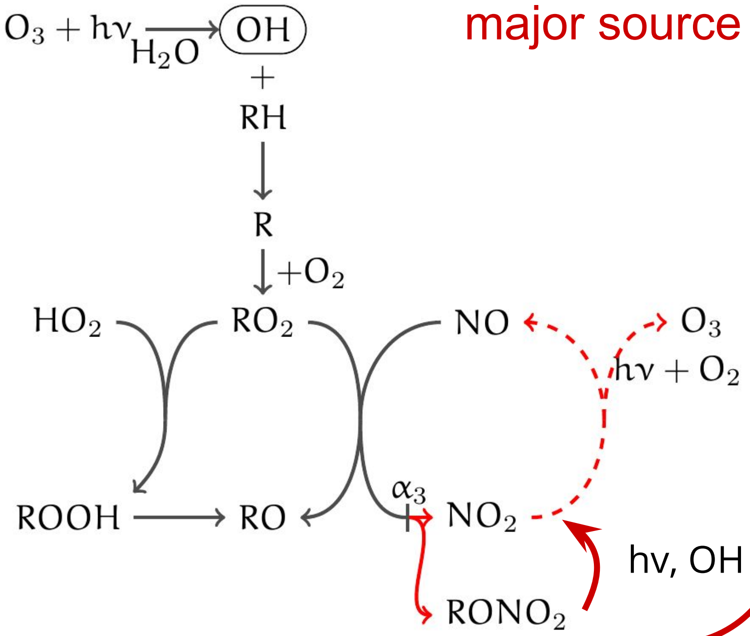


iso-propyl nitrate ($iPrONO_2$)

Introduction

major source



secondary sources

$RONO_2$

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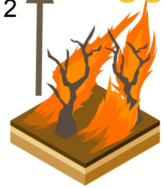

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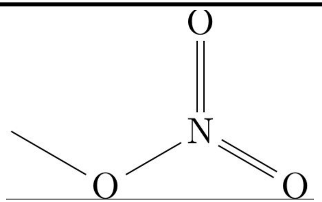

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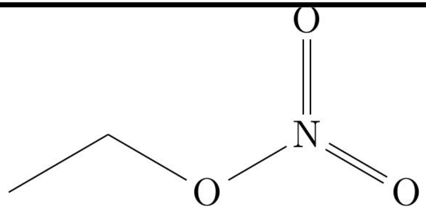

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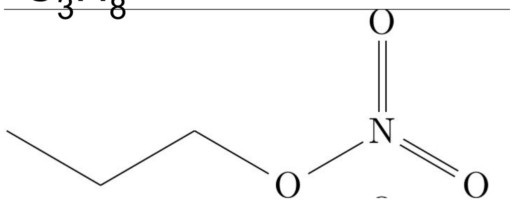

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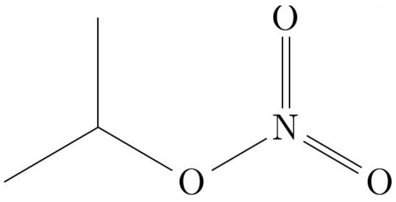

iso-propyl nitrate ($iPrONO_2$)

Global 3D modelling studies with $RONO_2$ so far...

Study	Model name	Model type	Simulation	Chemical scheme
Neu2008	UCI	CTM	year 2000	Wild2003
Williams2014	TM5	CTM	year 2008	CB05
Khan2015	STOCHEM-CRI	CTM	year 1998	CRI v2-R5
Fisher2018	GEOS-Chem	CTM	year 2013	GEOS-Chem
this study	UM-UKCA	CCM	10-year mean	CheST

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All studies had a different representation of $RONO_2$ sources

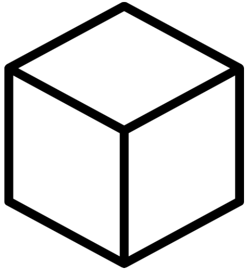
Objectives

- develop a chemical mechanism with C_1-C_3 $RONO_2$
- test it against a benchmark
- implement the mechanism into a global 3D model
- add oceanic emissions
- add biomass burning emissions

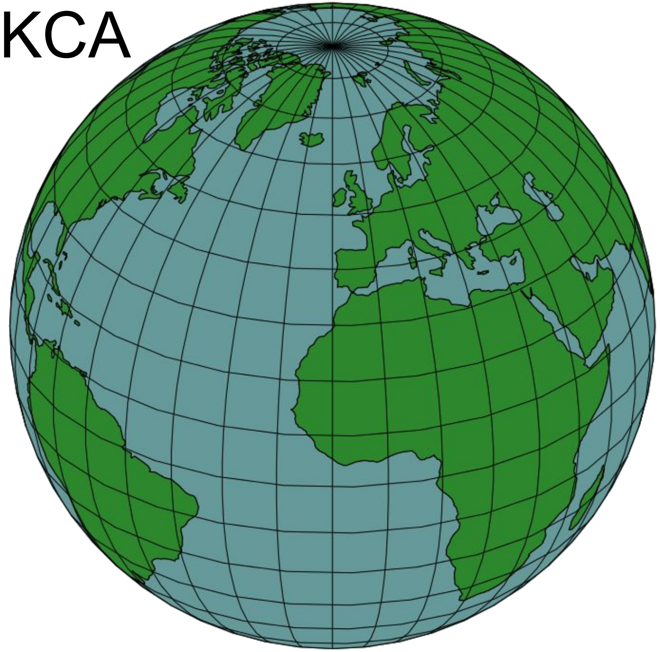
Methods

Methods

Box model



UM-UKCA



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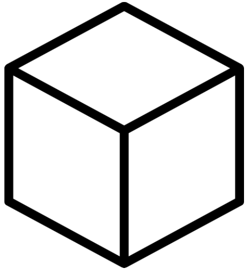

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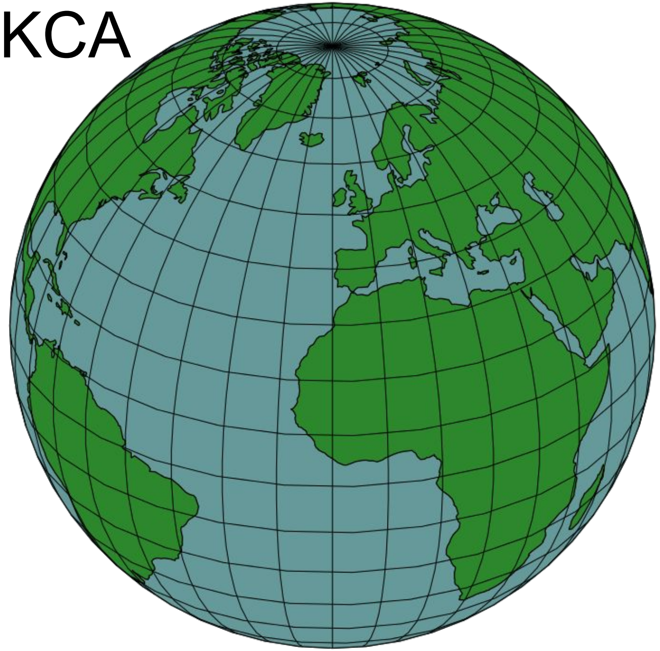
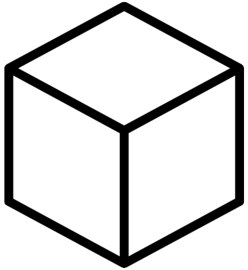


CheST

Methods

Box model



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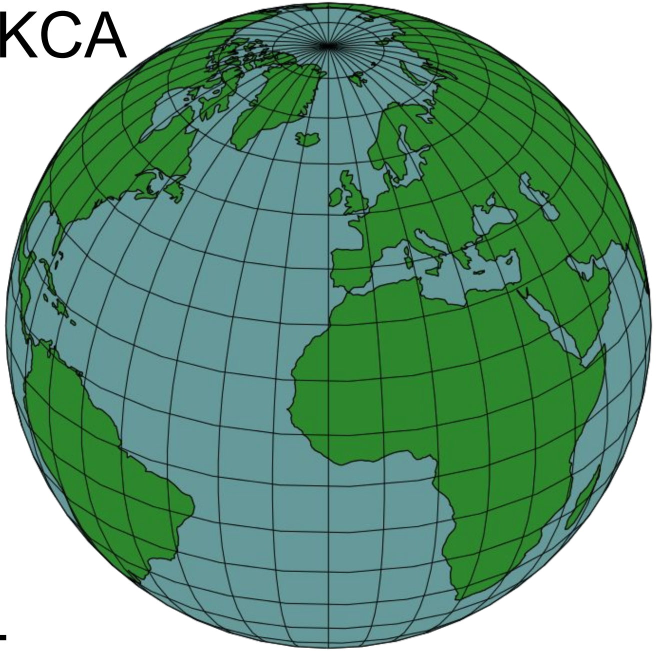


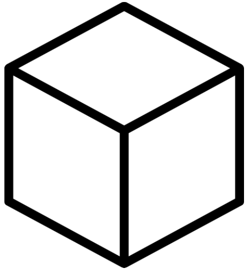
CheT: inorganic chemistry + C_1-C_3 alkanes + isoprene

CheST

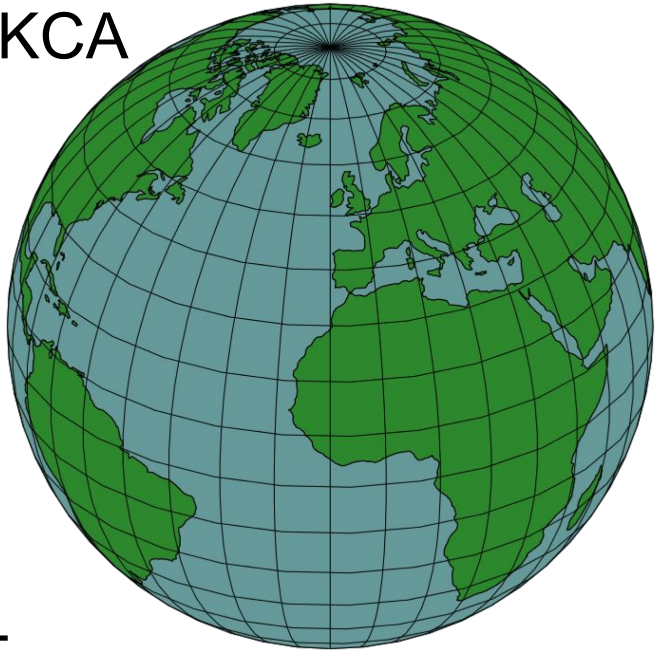
Methods

Box model

testing against MCM*



UM-UKCA



CheST

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*Master Chemical Mechanism

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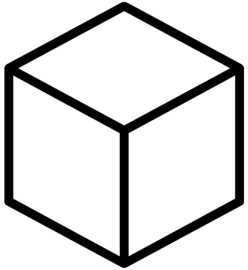

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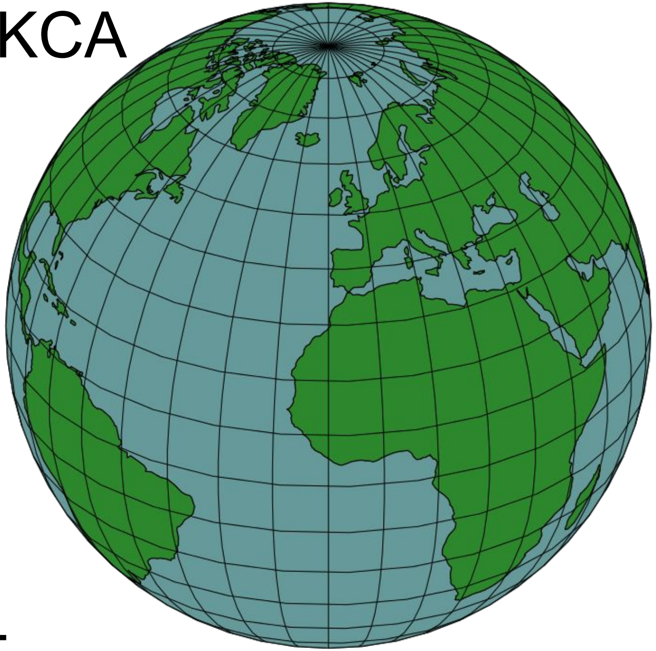

CheST

CheT: inorganic chemistry + C_1-C_3 alkanes + isoprene

*Master Chemical Mechanism

Implemented C_1-C_3 $RONO_2$

- after updating CheT chemical kinetics
- after deciding on $PrONO_2$ chemistry

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2. EtOO + NO = **$EtONO_2$**
3. nPrOO + NO = **$nPrONO_2$**
4. iPrOO + NO = **$iPrONO_2$**
5. $MeONO_2$ + hv = HCHO + HO_2 + NO_2
6. $EtONO_2$ + hv = MeCHO + HO_2 + NO_2
7. $nPrONO_2$ + hv = EtCHO + HO_2 + NO_2
8. $iPrONO_2$ + hv = Me2CO + HO_2 + NO_2
9. $MeONO_2$ + OH = HCHO + NO_2
10. $EtONO_2$ + OH = MeCHO + NO_2
11. $nPrONO_2$ + OH = EtCHO + NO_2
12. $iPrONO_2$ + OH = Me2CO + NO_2

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11. $nPrONO_2$ + OH = EtCHO + NO_2
12. $iPrONO_2$ + OH = Me2CO + NO_2

} exactly like in MCM

UKCA experiments

UKCA configuration

Version	7.3
Resolution	2.5°×3.75°, 60 levels
Meteorology	free running
Emissions	RCP8.5 scenario
Boundary conditions	SSTs, sea-ice annual cycle
Initial conditions	year 2000
Run lengths	10 years

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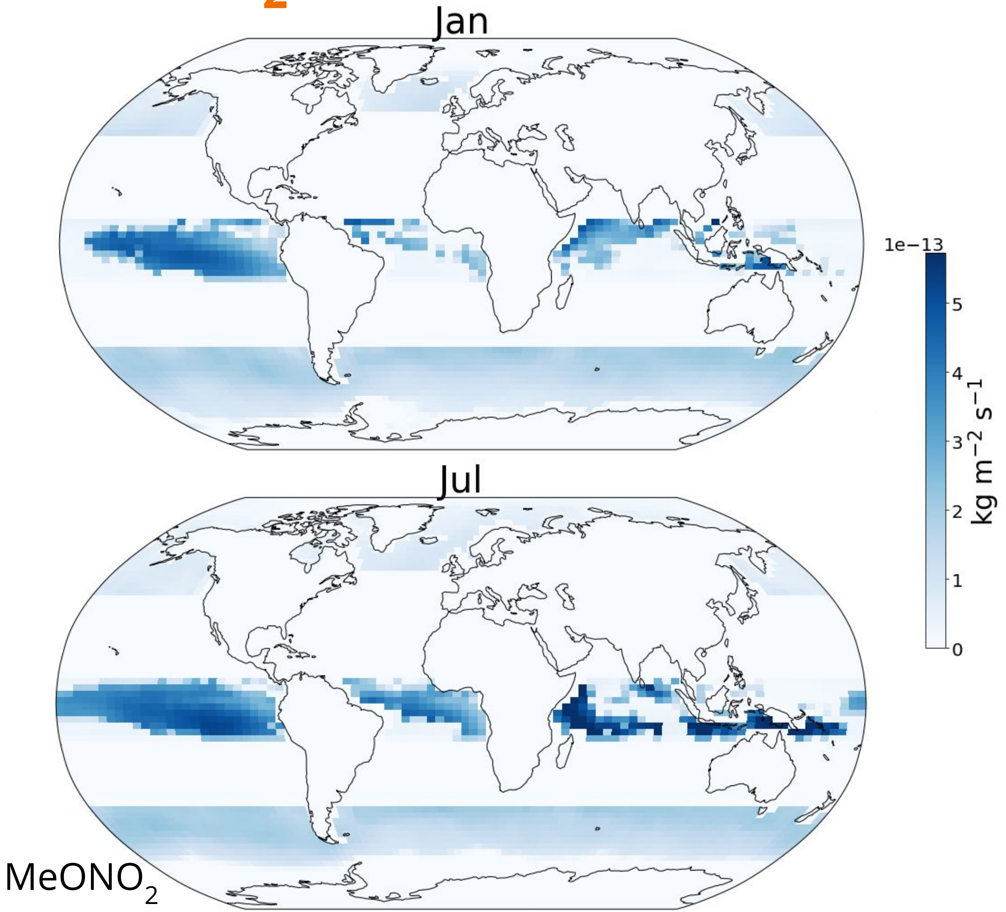
Are changes in the model chemical state statistically significant?

- use perpetual year simulations

UKCA experiments

Experiment	Description
BASE	Updated CheST without $MeONO_2$
OCEAN	C_1-C_2 $RONO_2$ oceanic emissions & photochemical loss
BB	C_1-C_3 $RONO_2$ biomass burning emissions & photochemical loss
CHEM* (historical)	$MeONO_2$ photochemical production & loss
$RONO_2$ dry deposition switched on in all experiments except CHEM*	

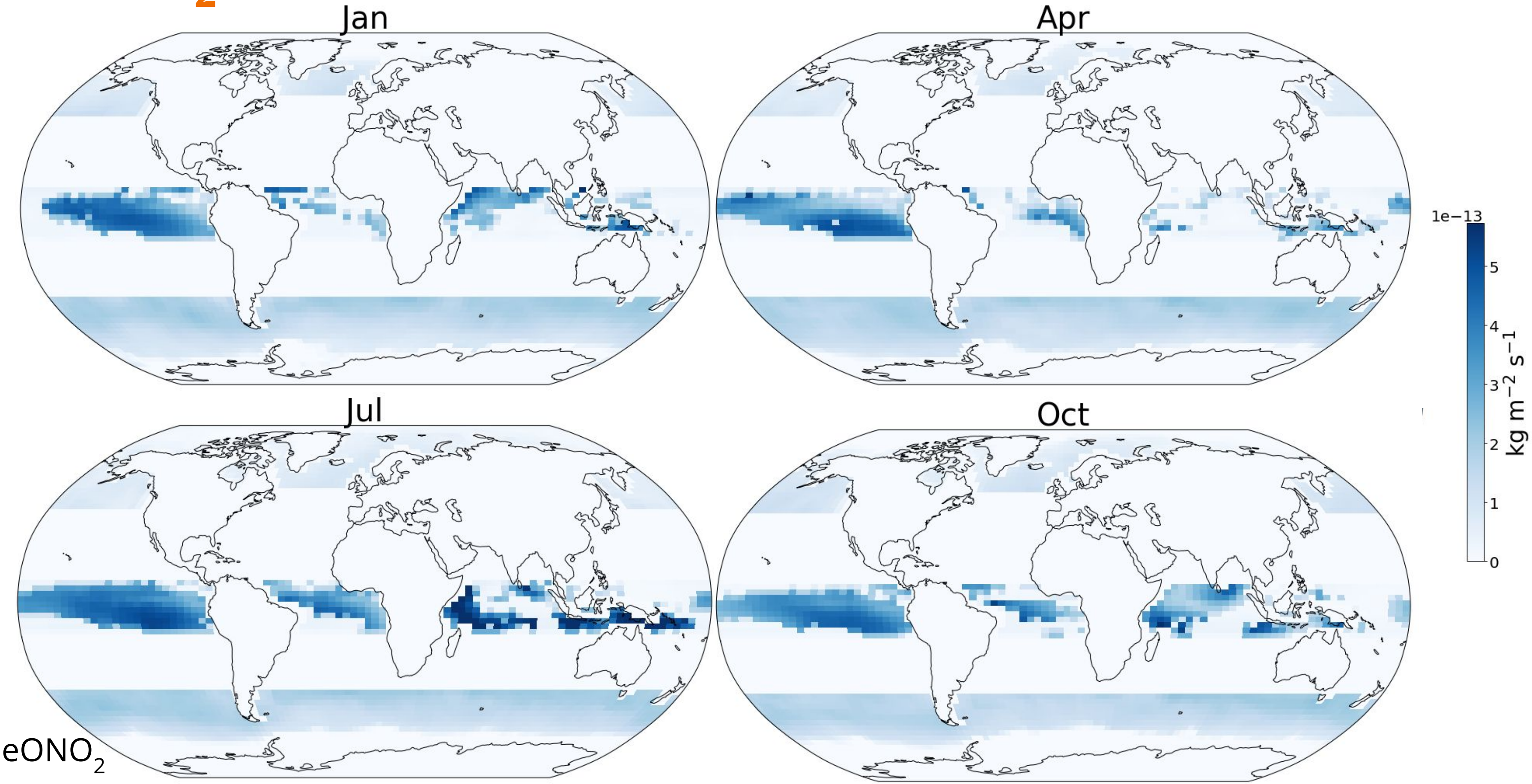
$RONO_2$ oceanic emissions



- In GEOS-Chem, Fisher et al. (2018) implemented **C_1-C_2 $RONO_2$ air-sea exchange**
- it was driven by changes in:
  - wind speed
  - SST
  - nitrite availability
- included seasonal and spatial variability

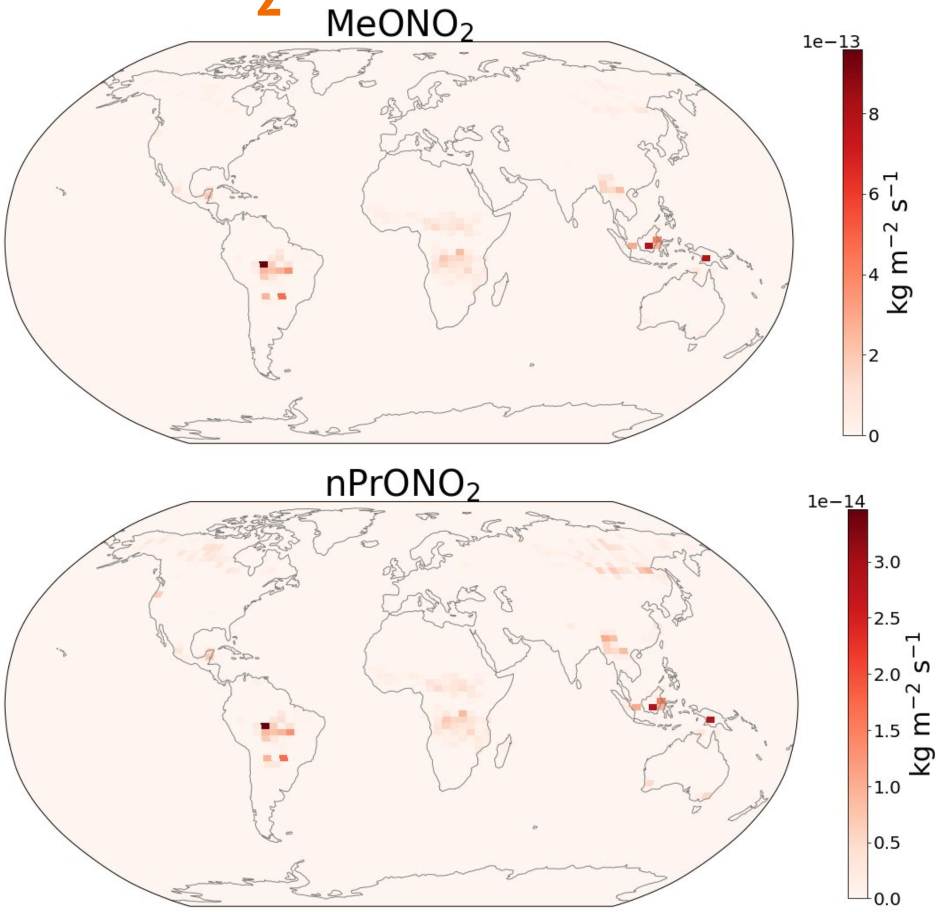
We implemented C_1-C_2 $RONO_2$ oceanic emissions modelled by GEOS-Chem into UKCA.

$RONO_2$ oceanic emissions



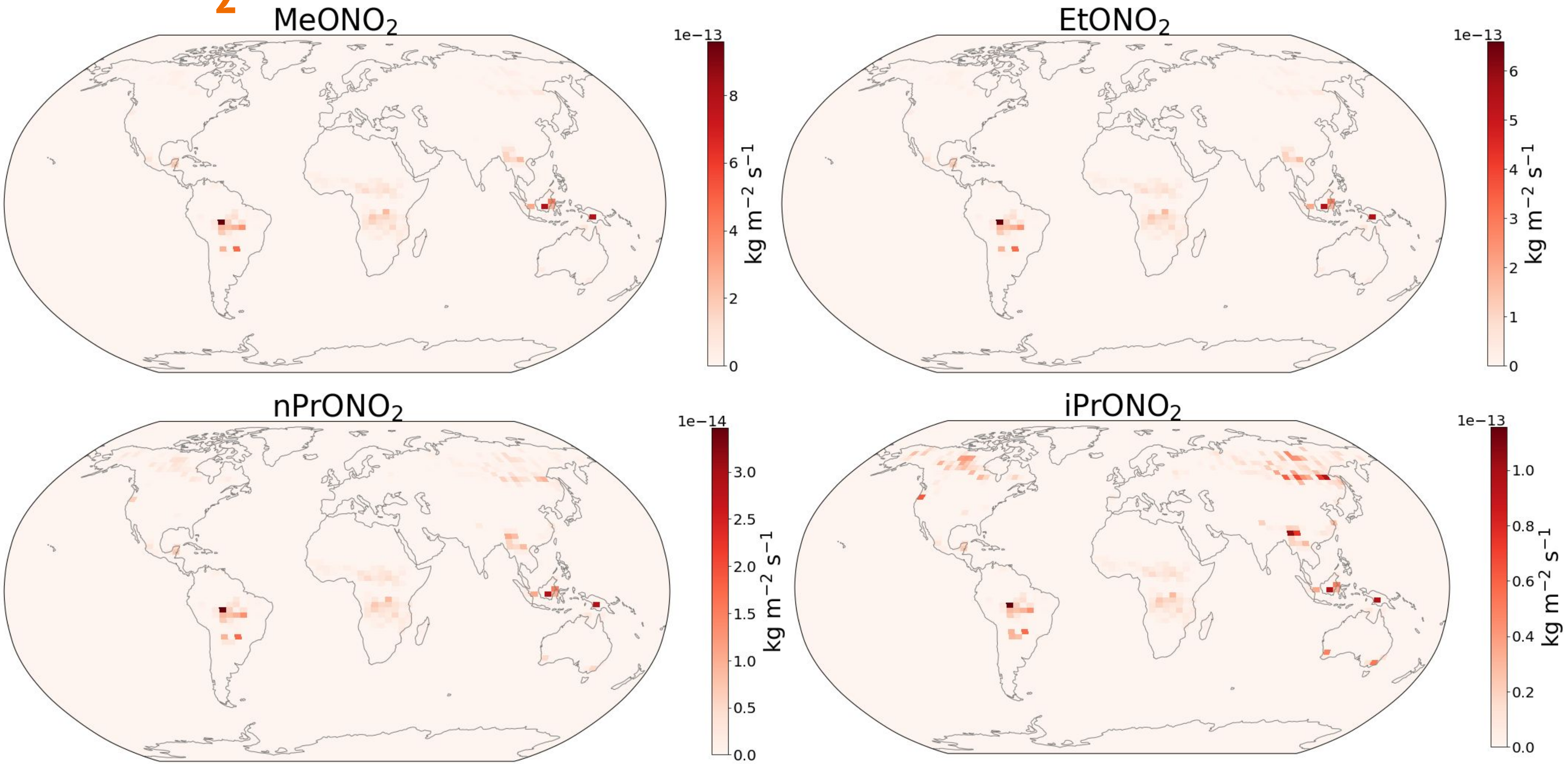
$MeONO_2$

$RONO_2$ biomass burning emissions



- Used Global Fire Emissions Database (GFED) data on dry matter emissions
- Applied emission factors for C_1-C_3 $RONO_2$ from Akagi et al. (2011) for **fires in**:
  - **tropical forest**
  - **savanna**
  - **boreal forest**
  - **extratropical forest**
- Calculated 20-year mean monthly emissions
- implemented into UKCA

$RONO_2$ biomass burning emissions



Global $RONO_2$ emissions per year

Emissions, Gg N yr^{-1}	$MeONO_2$	$EtONO_2$	$nPrONO_2$	$iPrONO_2$
oceanic	141	24	-	-
biomass burning	10	5	0.3	2

Simpson et al. (2002): C_1-C_4 $RONO_2$ BB emissions: ~18 Gg N yr^{-1}

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For comparison:
Nault et al. (2017): lighting NO_x emissions: 2–9 Tg N yr^{-1}
Lee at al. (1997): all NO_x emissions: 44 Tg N yr^{-1}

Global $RONO_2$ emissions per year ... do these matter?

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Validation

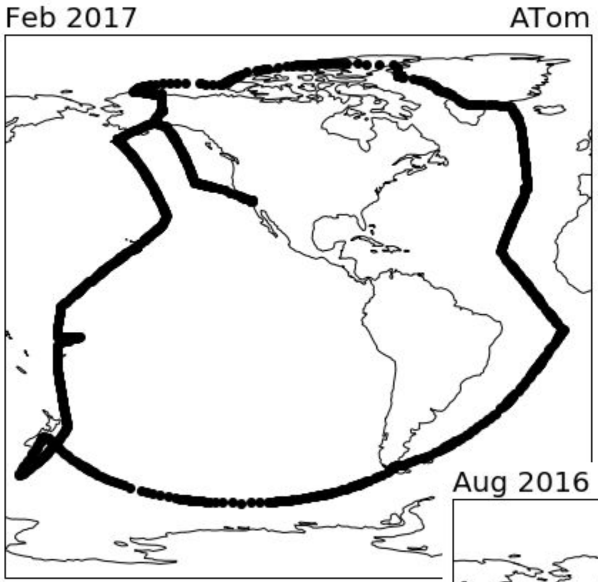
Validation

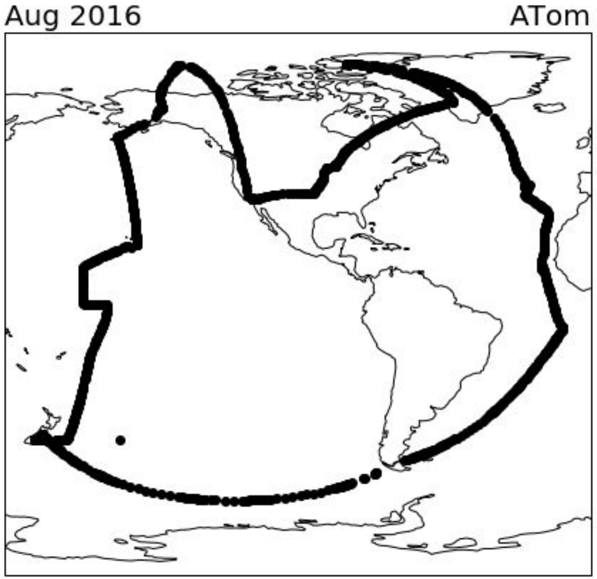
NASA's Atmospheric Tomography (ATom) mission

- flights occurred in each of 4 seasons from 2016 to 2018
- profiles from 0.2 to 12 km

Here we used:

- ATom-1 (Jul-Aug 2016)
- ATom-2 (Jan-Feb 2017)





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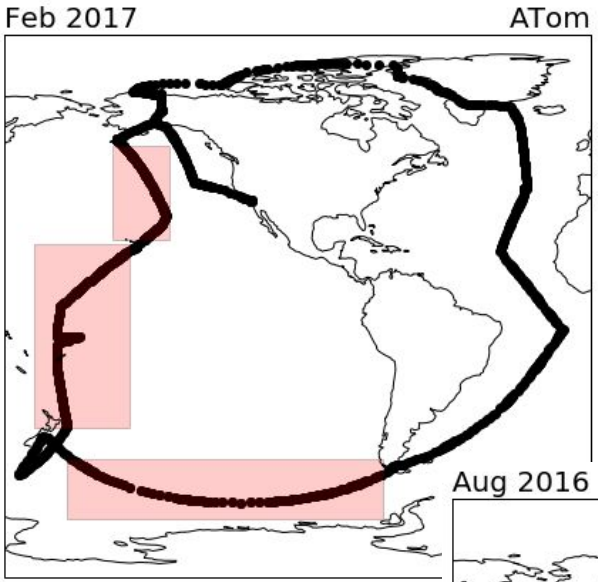

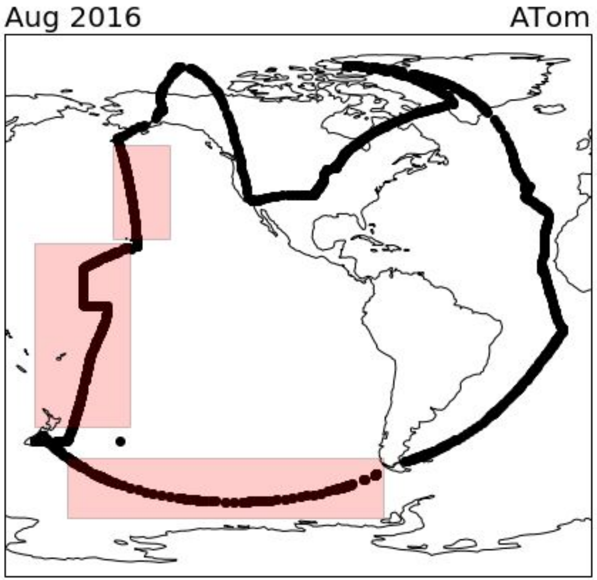

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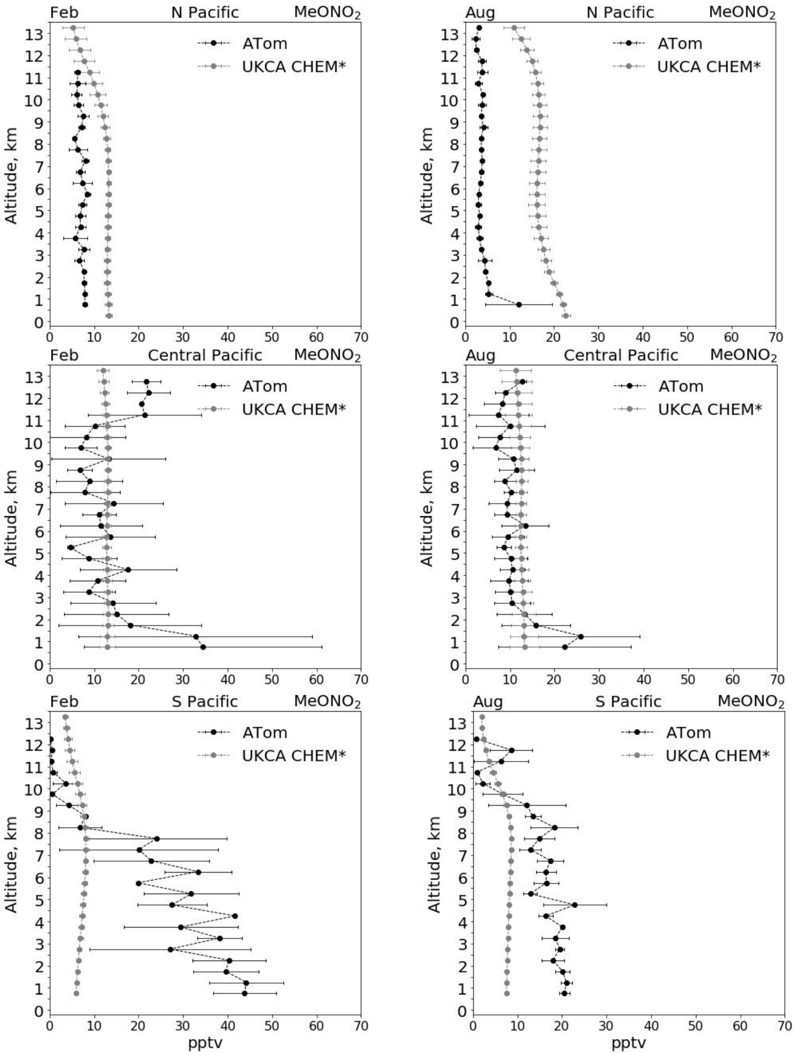
Feb
N Pacific
MeONO2
ATom
UKCA CHEM*
Altitude, km
Aug
N Pacific
MeONO2
Feb
Central Pacific
MeONO2
Aug
Central Pacific
MeONO2
Feb
S Pacific
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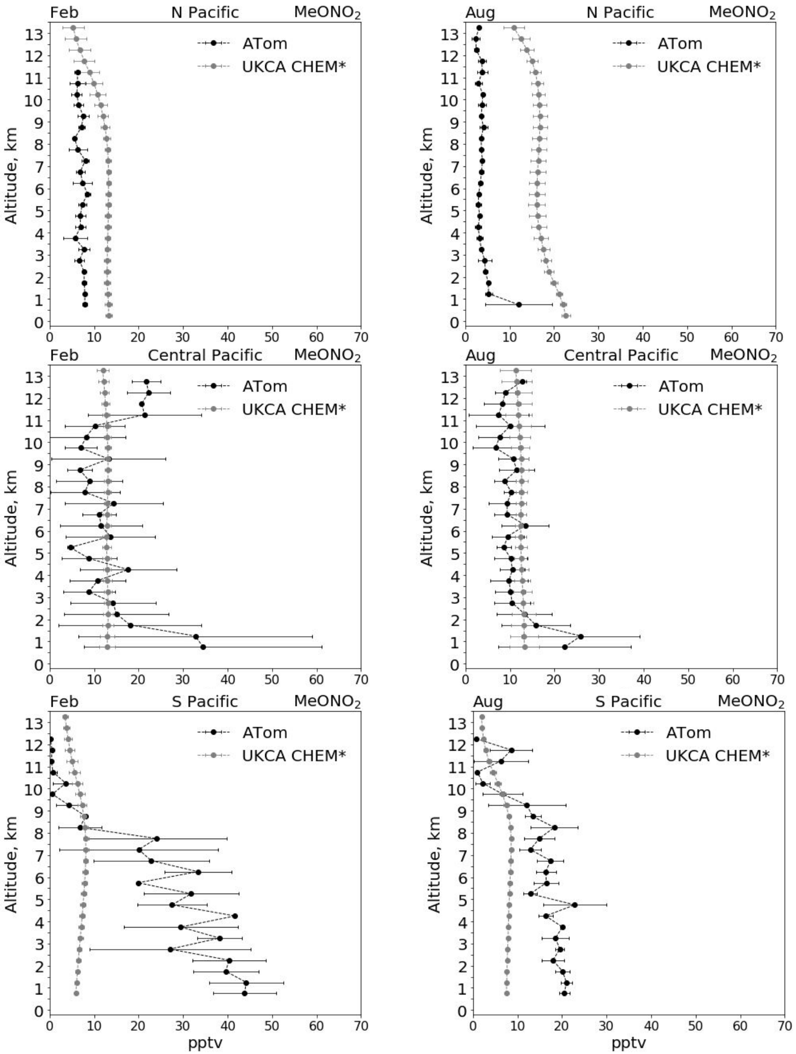
Aug
S Pacific
MeONO2
pptv

Validation

- CHEM* overestimates $MeONO_2$ by ~5 ppt in Feb and by ~10 ppt in Aug in the NH
    - high CH_4?
    - high NO_x?
    - insufficient $MeONO_2$ loss?
- UKCA's $MeONO_2$ seasonality is opposite to ATom's
- CHEM* suggests a missing oceanic source over the equator and Southern Ocean



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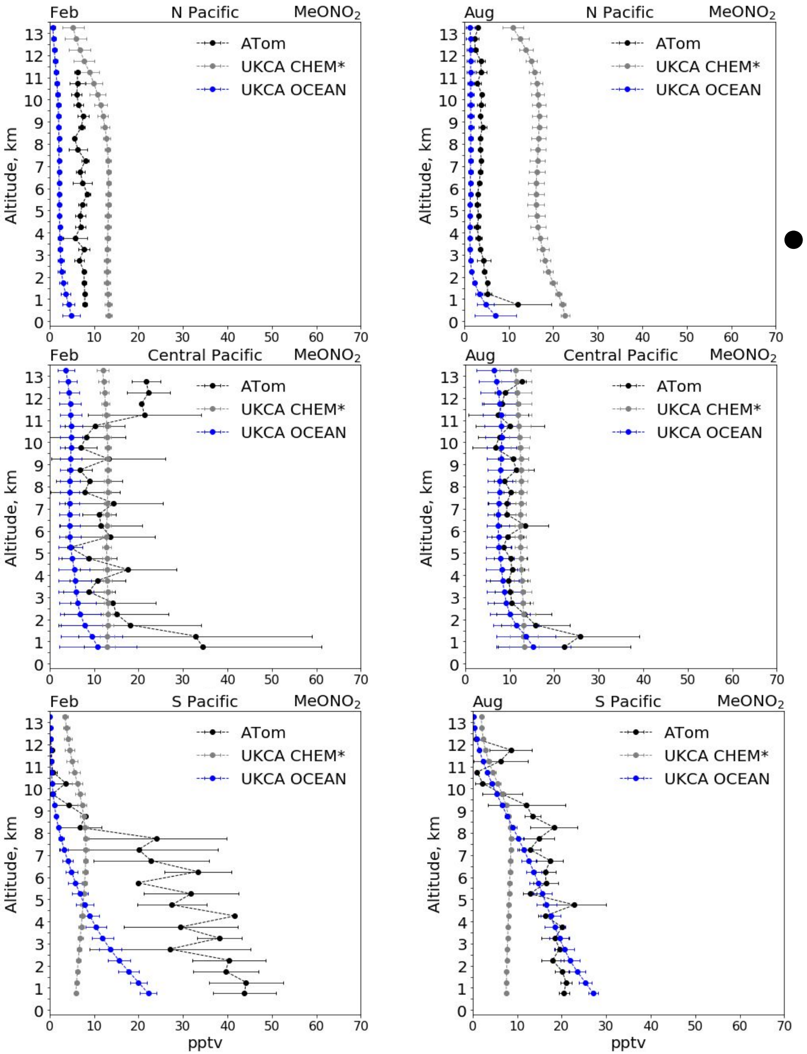

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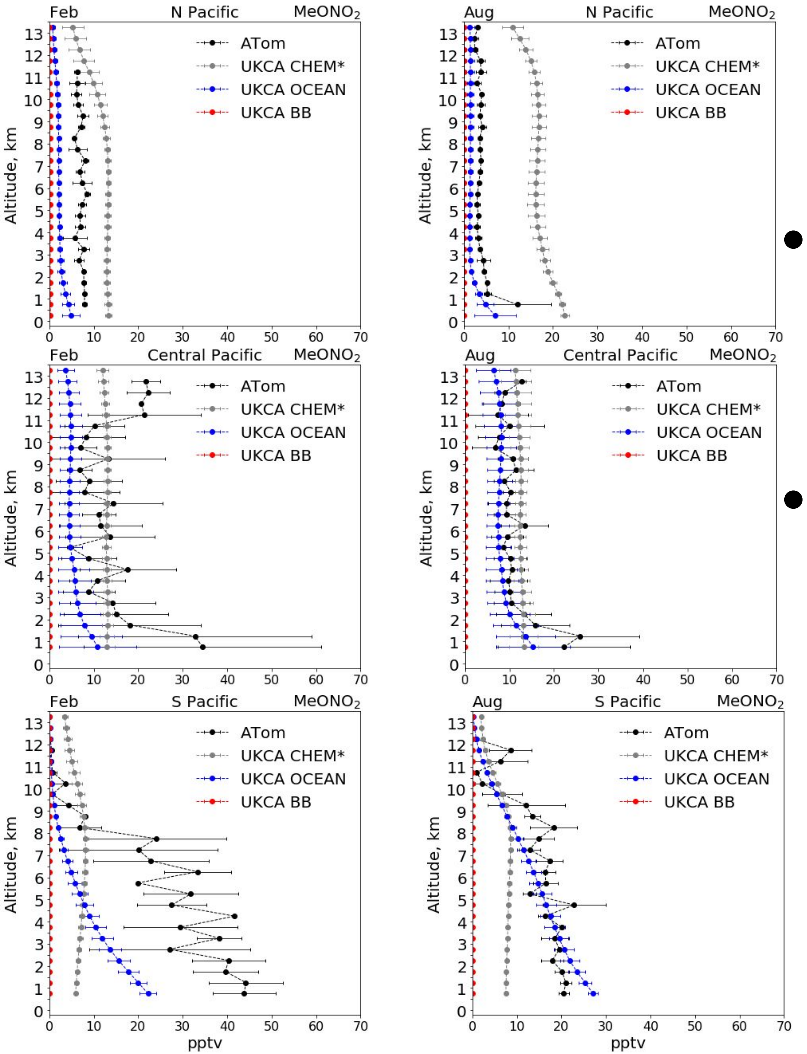

- OCEAN produces vertical profiles closer in shape to the observed but with lower values
- BB $MeONO_2$ contribution is small

Impacts of $RONO_2$ chemistry

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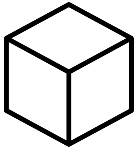

~CHEM

- $RONO_2$ photochemical production and loss lowered HO_x
  - O_3, OH, HO_2 were lower by 2% in runs with $RONO_2$ (without isoprene)
  - even smaller impact in runs with isoprene

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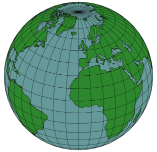

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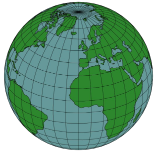
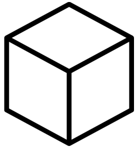
	OCEAN	BB
O_3 burden, Tg		
Williams et al. (2014)	335.3 (**+0.30%**)	
this study*	274.54 (**+0.46%**)	273.25 (**-0.007%**)
CH_4 lifetime, yr		
Neu et al. (2008)	9.28 (**-1.7%**)	
Williams et al. (2014)	8.40 (**-0.24**)	
this study*	9.47 (**-1.04%**)	9.572 (**-0.02%**)
*10-year average using 125 ppb ozonopause		

Impacts of $RONO_2$ chemistry





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All of these are global means, **but what happens locally**?

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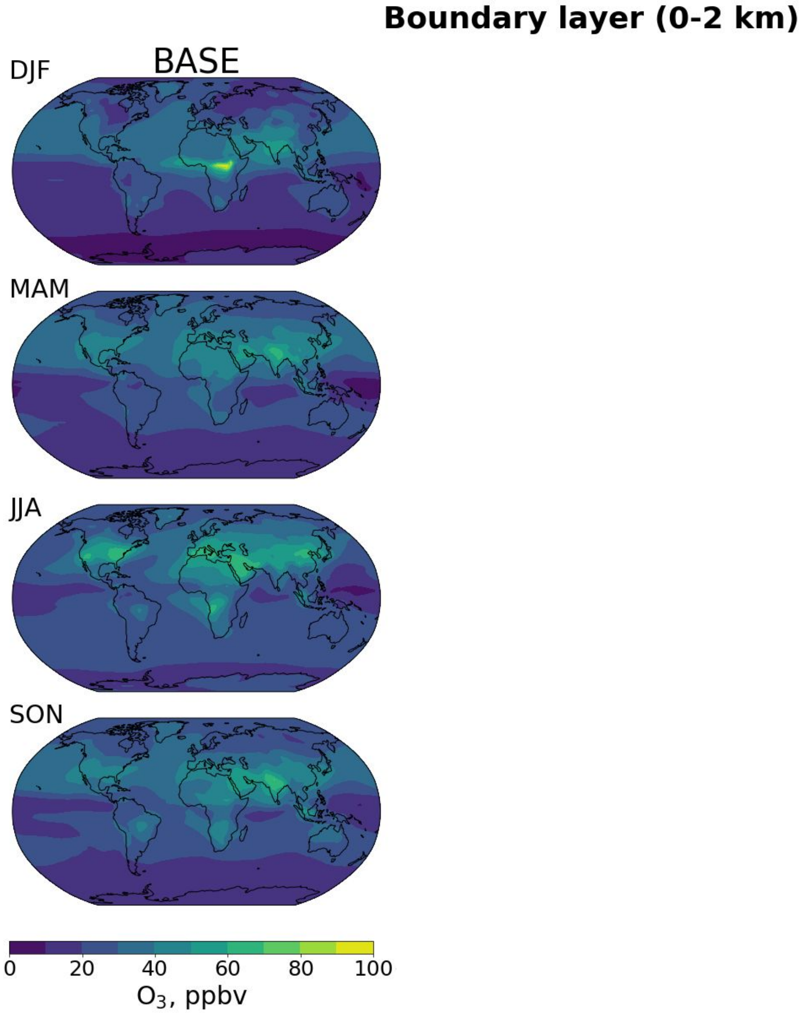
Impact of oceanic $RONO_2$ on O_3

Boundary layer (0-2 km)

Impact of oceanic $RONO_2$ on O_3



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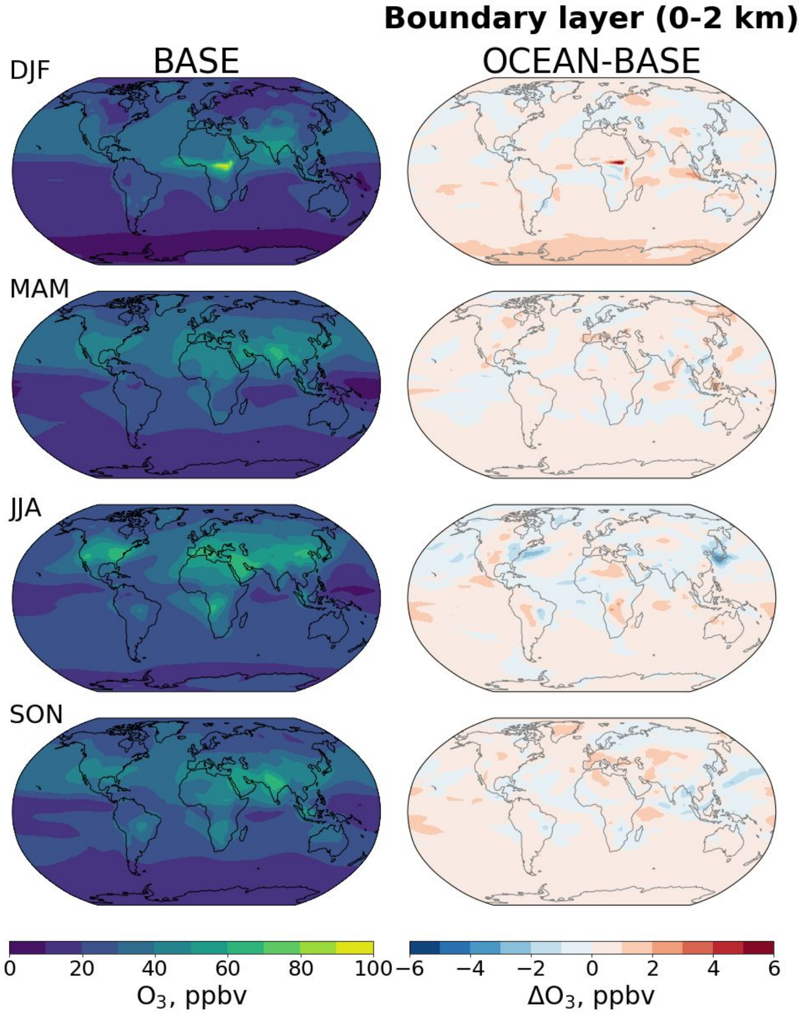

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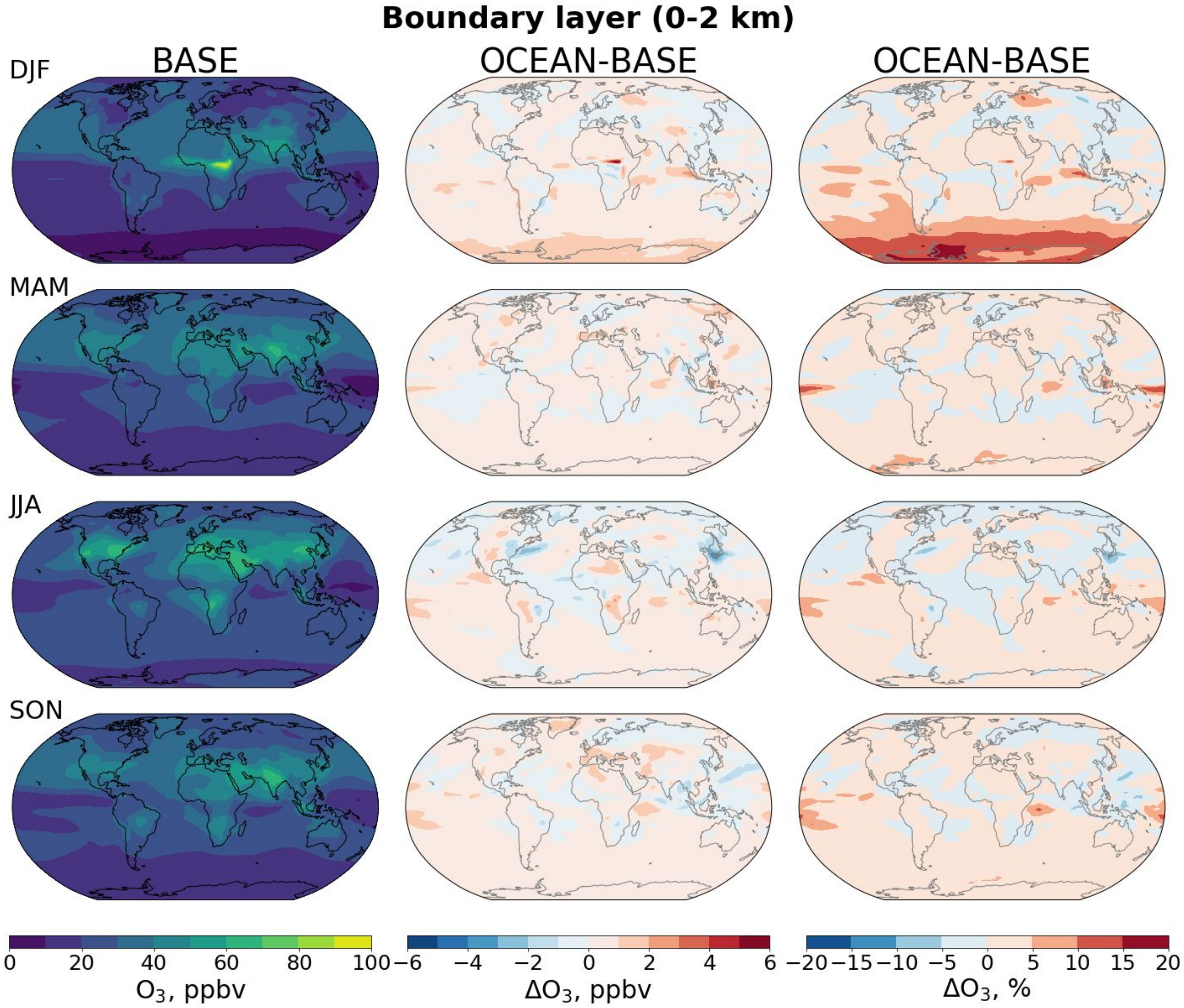
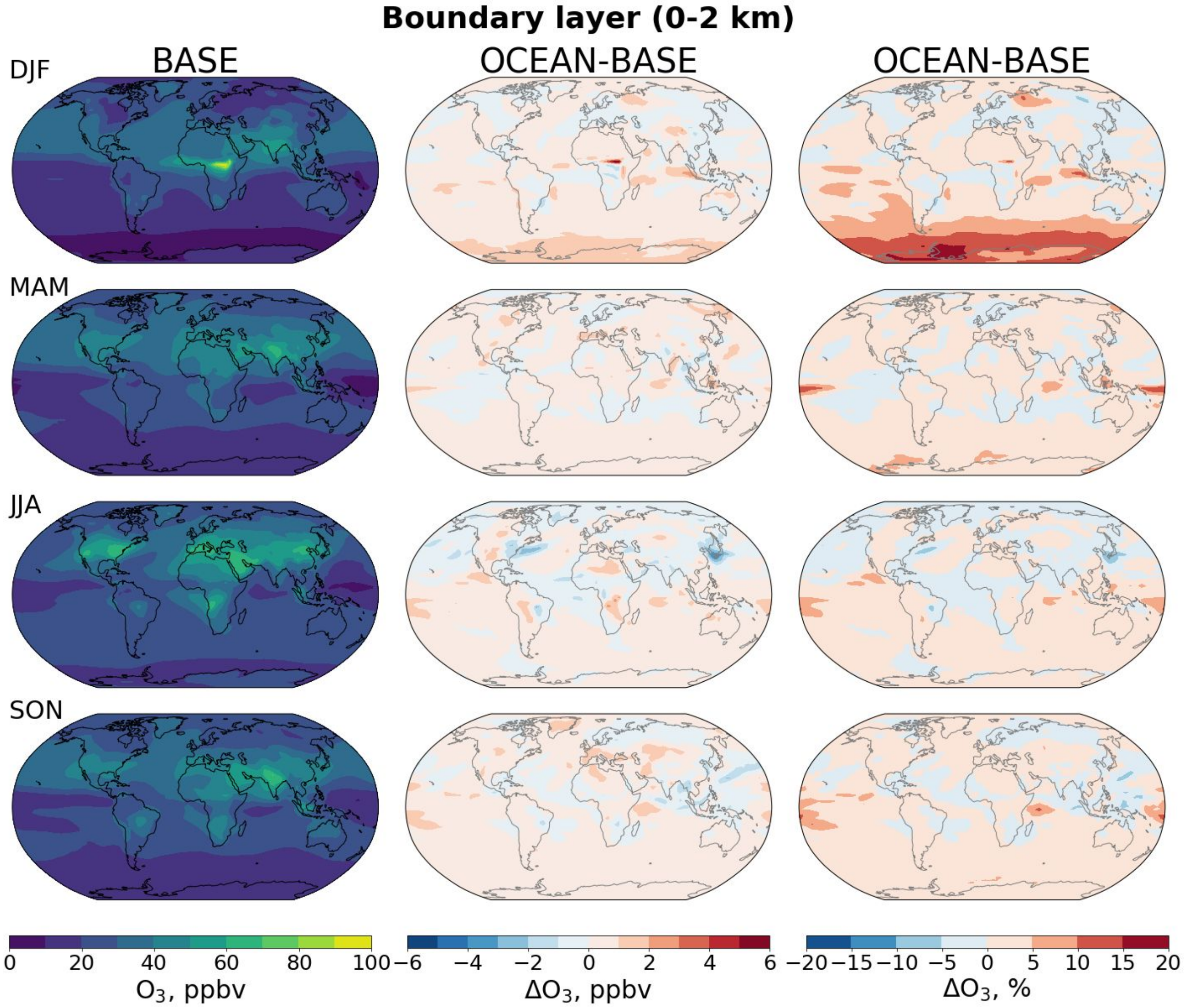


Impact of oceanic $RONO_2$ on O_3

- increase over the Southern Ocean by up to 20% (< 2 ppb)



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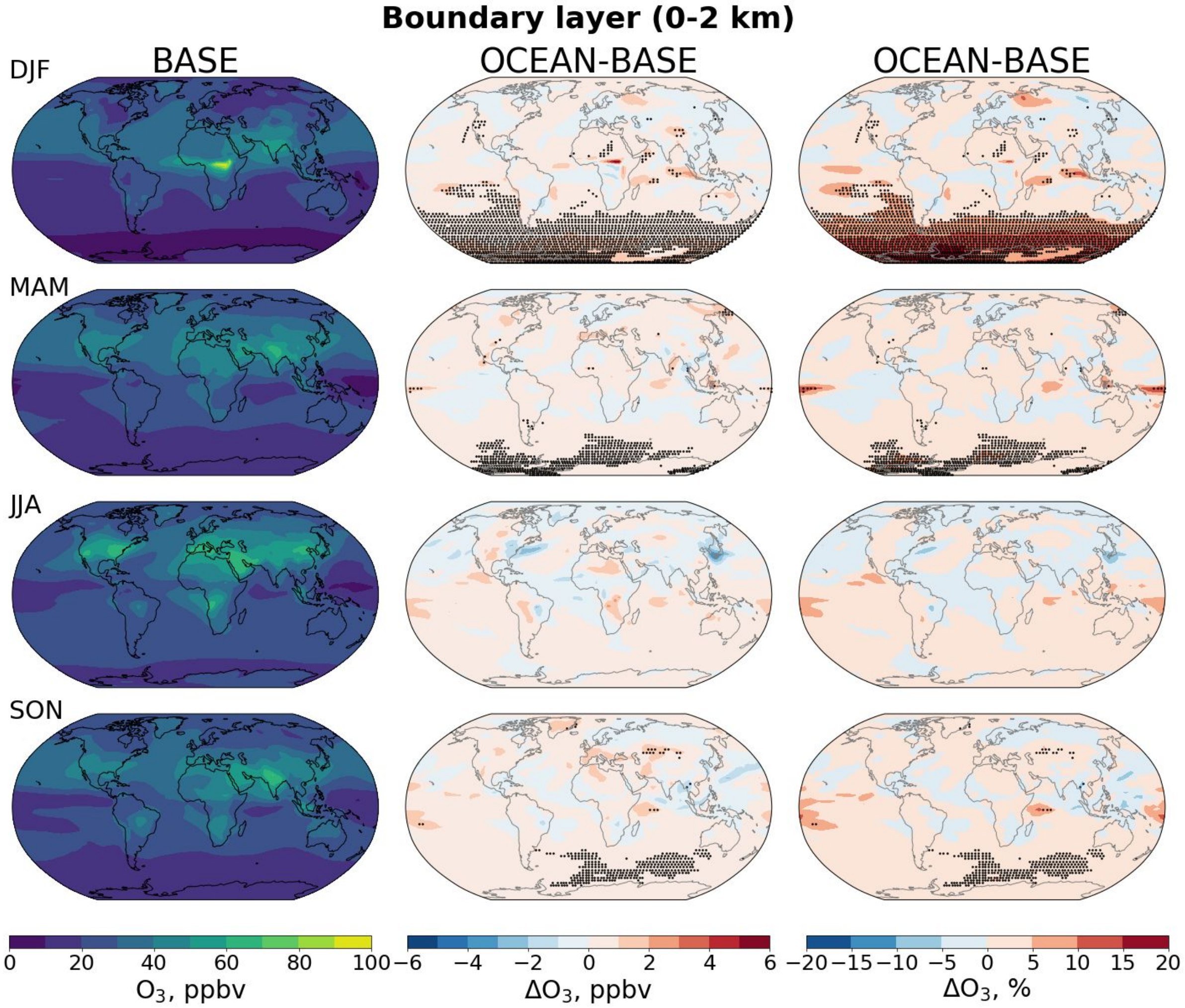

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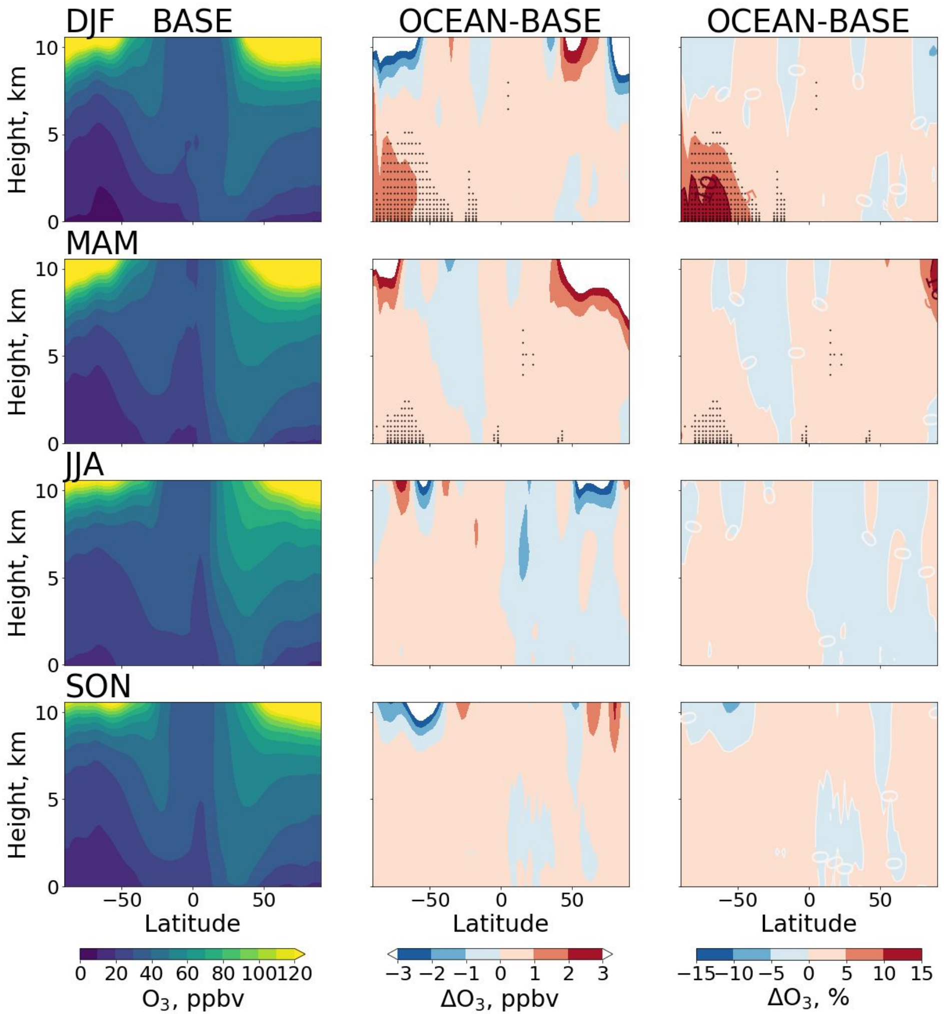
zonal mean (0-10 km)

Impact of oceanic $RONO_2$ on O_3

- increase over the Southern Ocean by up to 20% (< 2 ppb)
- statistically significant in all seasons except JJA
- signal persists up to 3-5 km in DJF and MAM

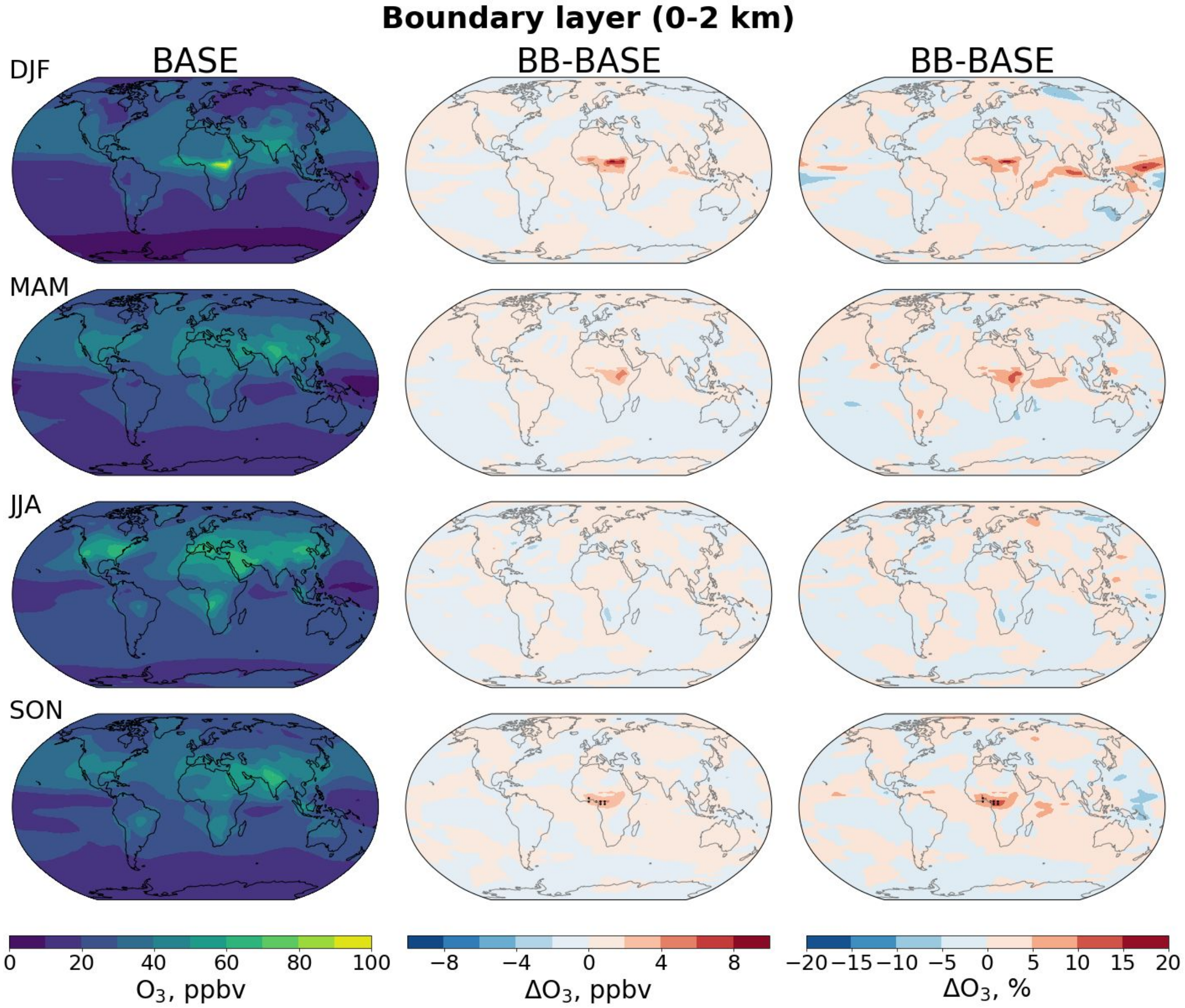


Impact of BB $RONO_2$ on O_3

Boundary layer (0-2 km)

Impact of BB $RONO_2$ on O_3

- increase over the equatorial Africa by up to 20% (< 6 ppb)



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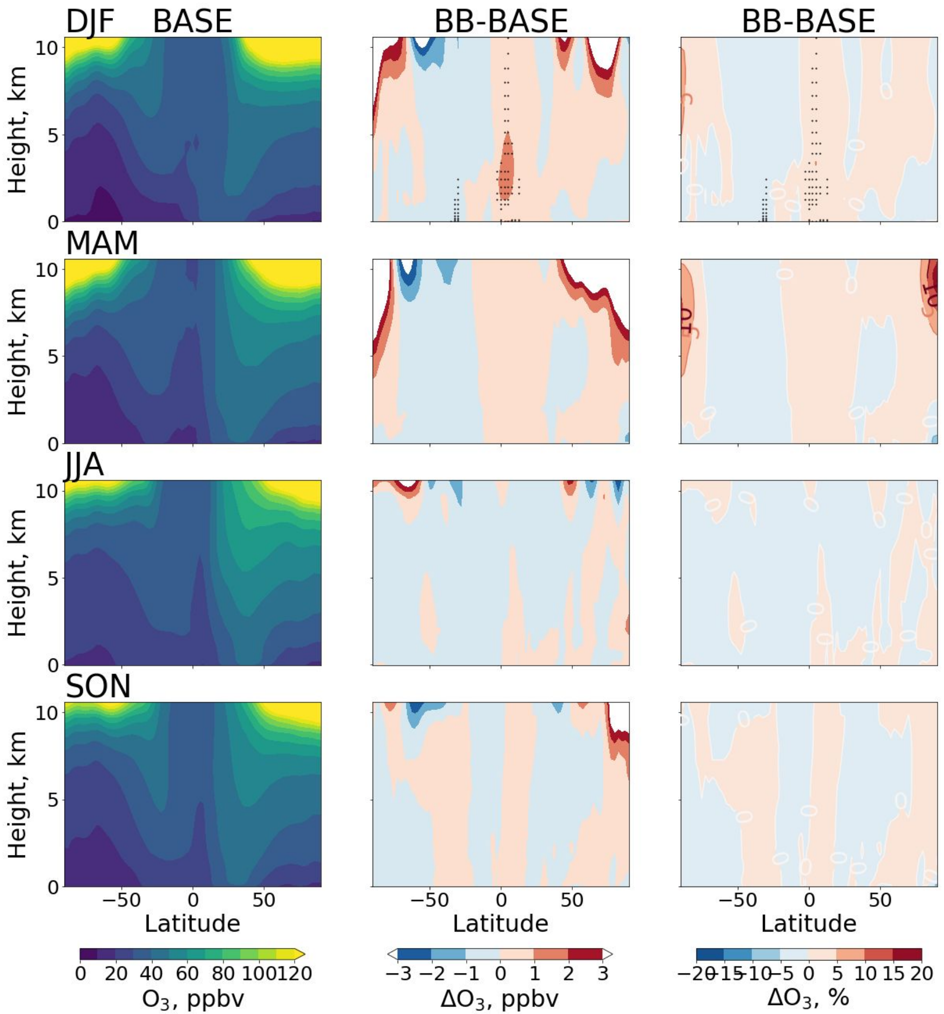

Conclusions

- We updated UKCA's CHeST chemical kinetics and added C_2-C_3 $RONO_2$ chemistry explicitly.
- When compared to ATom, UKCA overestimates $MeONO_2$, especially in August.
- Implemented monthly varying emissions of:
  - oceanic C_1-C_2 $RONO_2$ modelled by GEOS-Chem,
  - biomass burning C_1-C_3 $RONO_2$ derived from GFED.
- UKCA model state is sensitive to oceanic and biomass burning $RONO_2$ emissions:
  - Southern Ocean area is sensitive to oceanic $RONO_2$ emissions:
    - NO_x increases up to 160% (< 700 ppt),
    - O_3 increases by up to 20% (< 2 ppb) in DJF, MAM, SON.
  - equatorial Africa region is sensitive to $RONO_2$ biomass burning emissions:
    - NO_x increases by up to 80% (< 800 ppt),
    - O_3 increases by up to 20% (< 6 ppb) in DJF.

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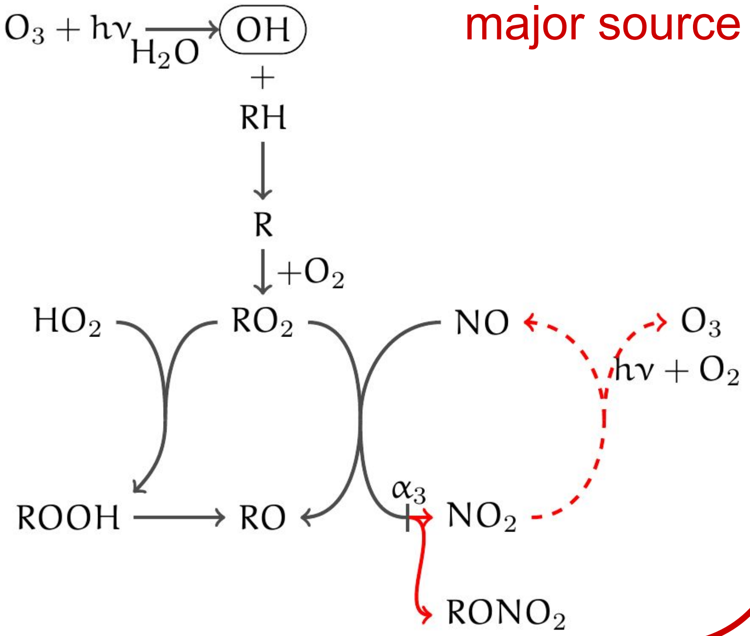
Thank you!

Extra

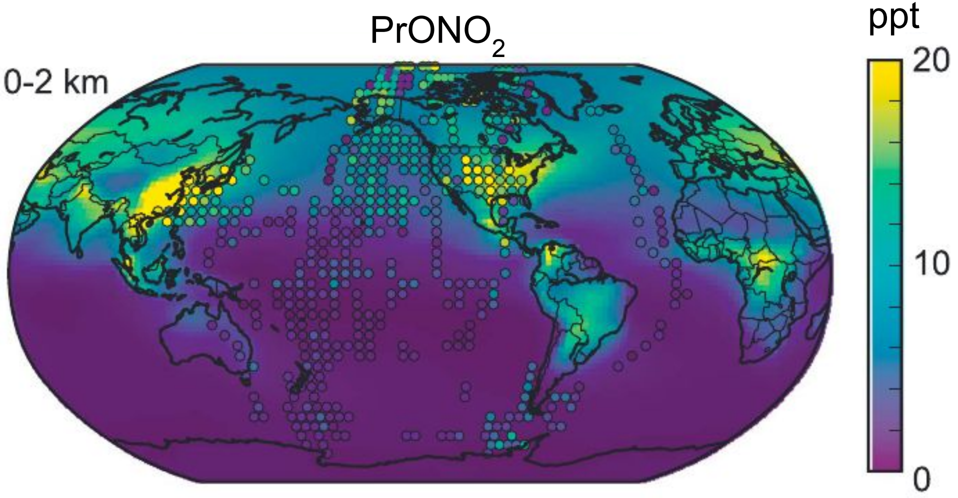
Introduction

major source



secondary sources

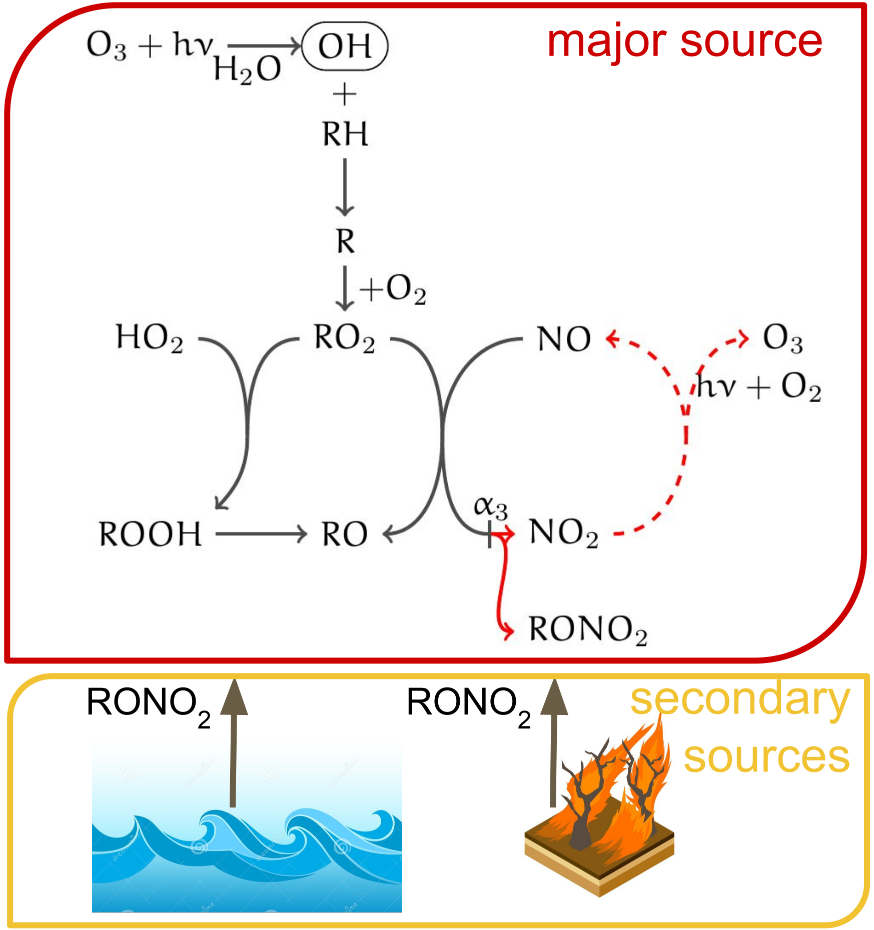
- $PrONO_2$ are produced mostly photochemically



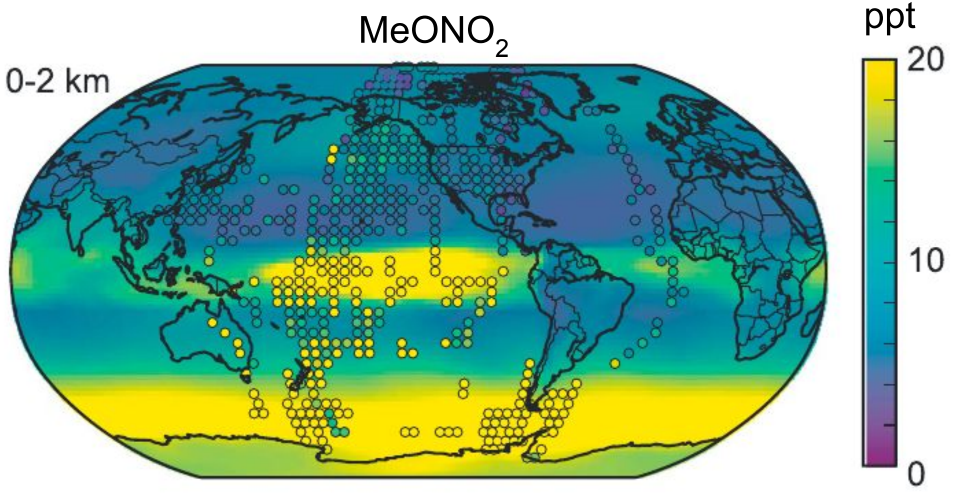
Annual mean distribution of $PrONO_2$.
20 years of aircraft observations were averaged over all flight days and over a horizontal resolution of 4°×5° for visibility.

Credit: Fisher et al. (2018)

Introduction



- $MeONO_2$ has strong oceanic sources in the Central Pacific and Southern Oceans



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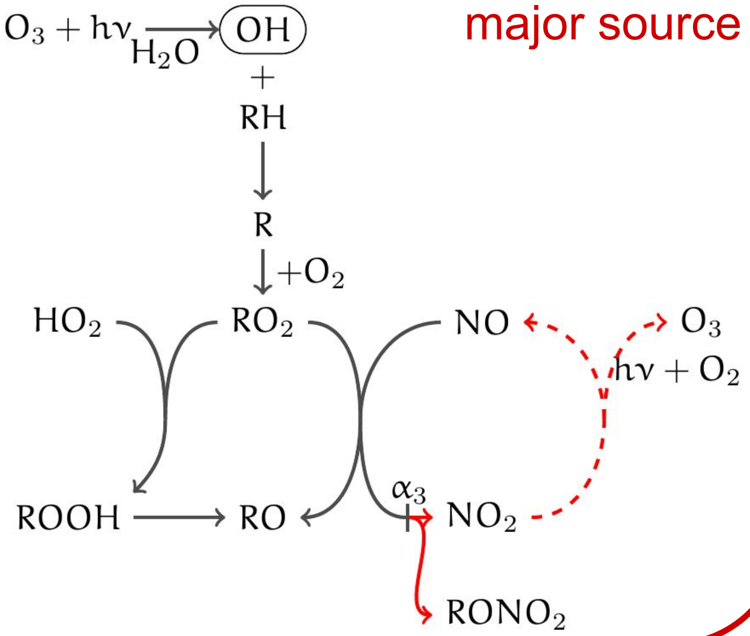
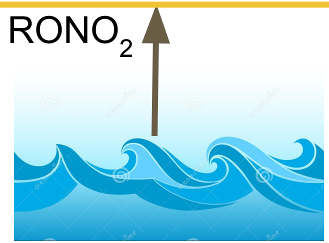
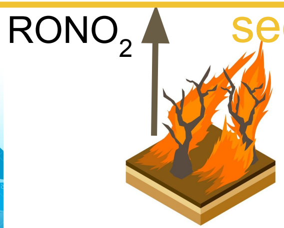
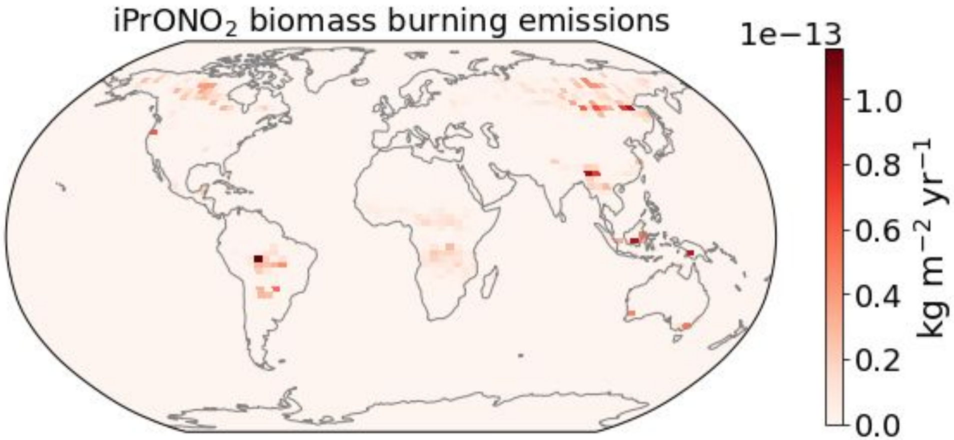






secondary sources

- $RONO_2$ biomass burning emissions depend on the type of fuel burned



20-year average annual mean distribution of $iPrONO_2$ biomass burning emissions derived from the GFED data (Akagi et al. (2011)).

this study

Implementation of C_1-C_3 $RONO_2$

	$MeONO_2$					$EtONO_2$					$nPrONO_2$					$iPrONO_2$				
	CH prod	CH loss	DD	OC	BB	CH prod	CH loss	DD	OC	BB	CH prod	CH loss	DD	OC	BB	CH prod	CH loss	DD	OC	BB
Neu2008																				
Williams 2014			WD	Neu		OR GNT R	OR GN TR	WD			OR GNT R	OR GN TR	WD			OR GNT R	OR GN TR	WD		
Khan2015				Neu	Simp son					Simp son					Simp son					Simp son
Fisher2018				air-s ea					air- sea					air- sea					air- sea	
this study				Fish er	GF ED				Fis her	GF ED				?	GF ED				?	GF ED

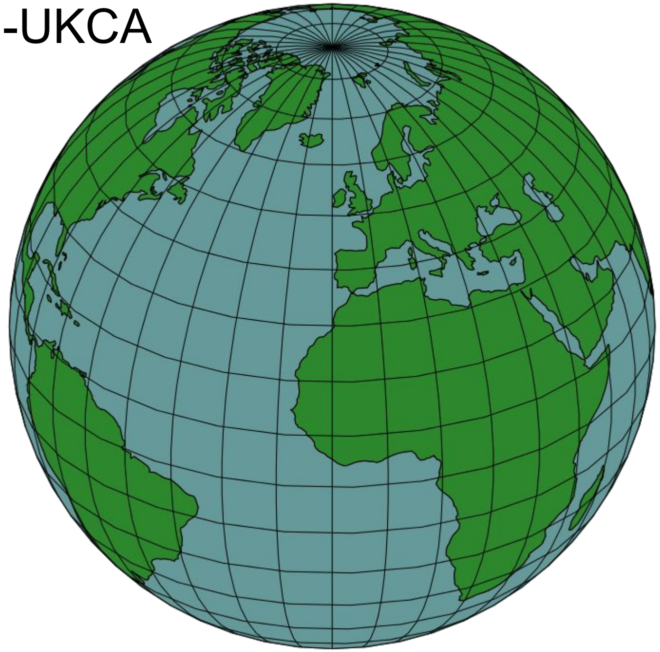
Steady state box model

Temperature	298 K
Pressure	1000 hPa
Relative humidity	50%
Cloud cover	No clouds
Julian day	172 (21 June)
Latitude	45N
Solar declination angle	23.44
Initial concentration	O3 40 ppb, CO 100 ppb, CH4 1800 ppb
Run time	6 months

Methods

Box model

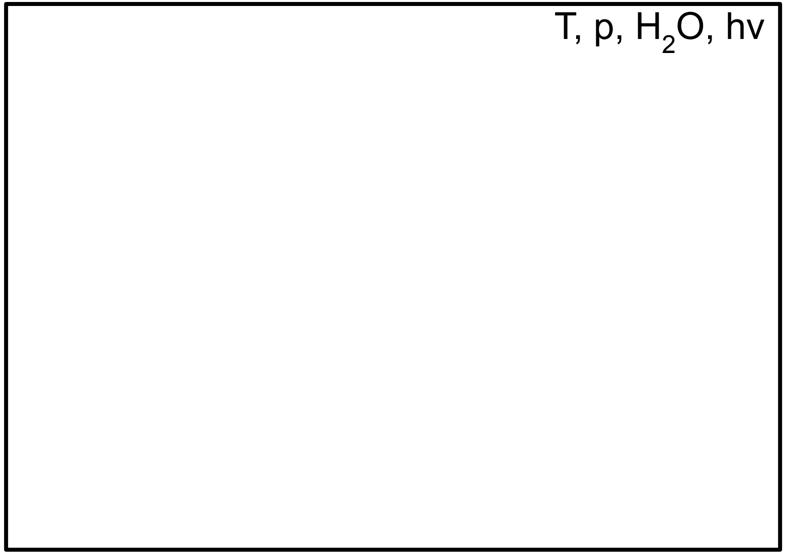
UM-UKCA



CheT

CheST: inorganic chemistry + C_1-C_3 alkanes + isoprene

Steady state box model



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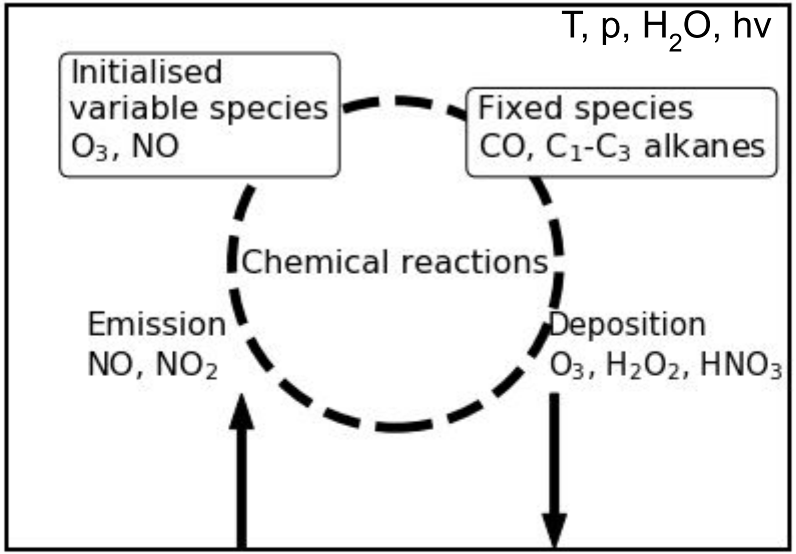

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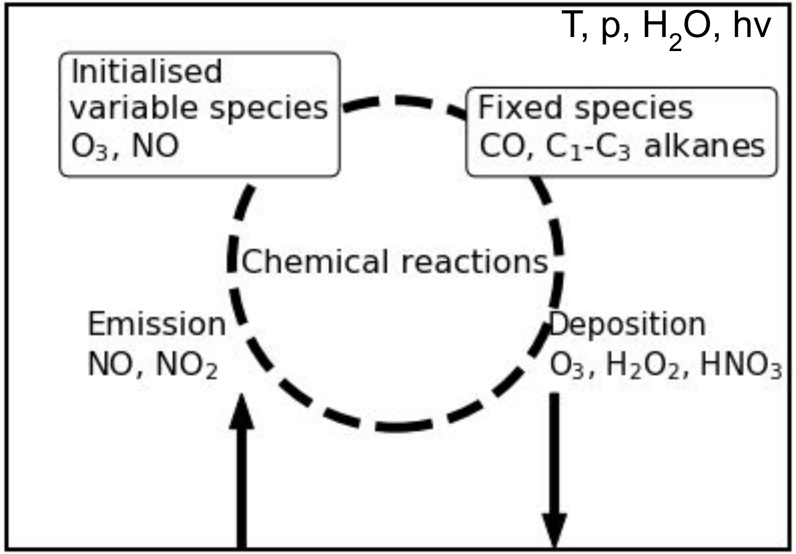
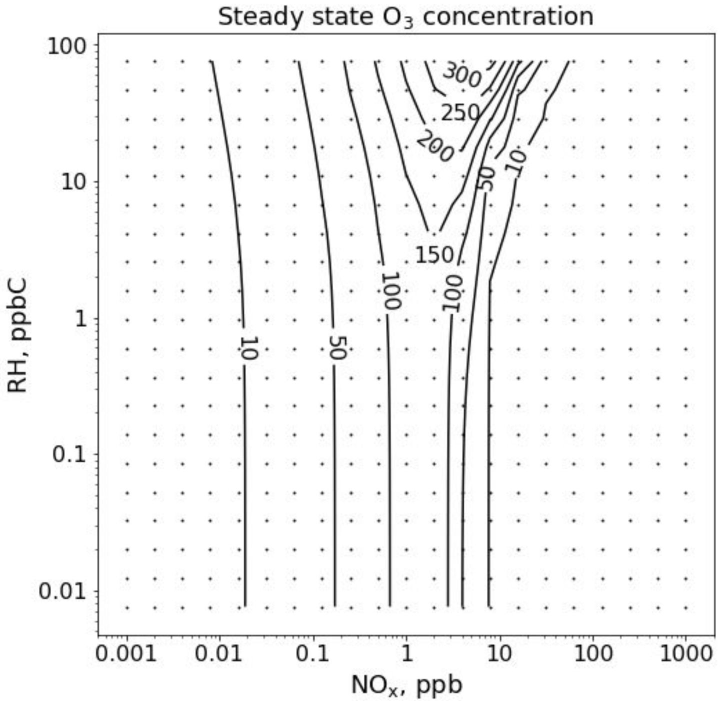
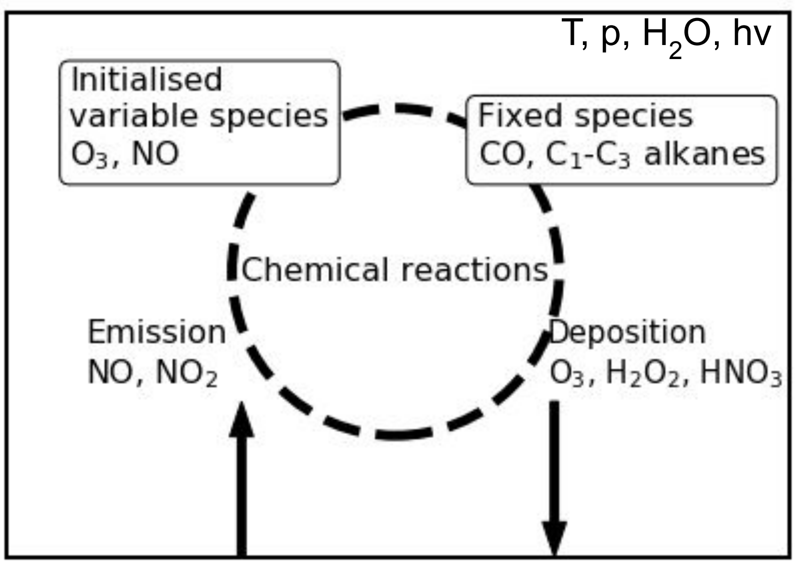
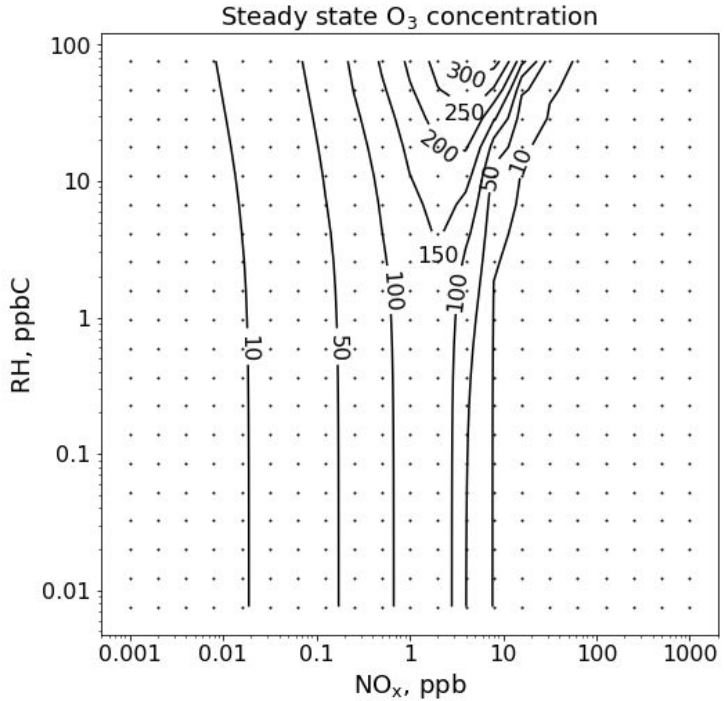




- To reach steady state, O_3 precursors (NO_x and NMHC) were kept constant

Steady state box model





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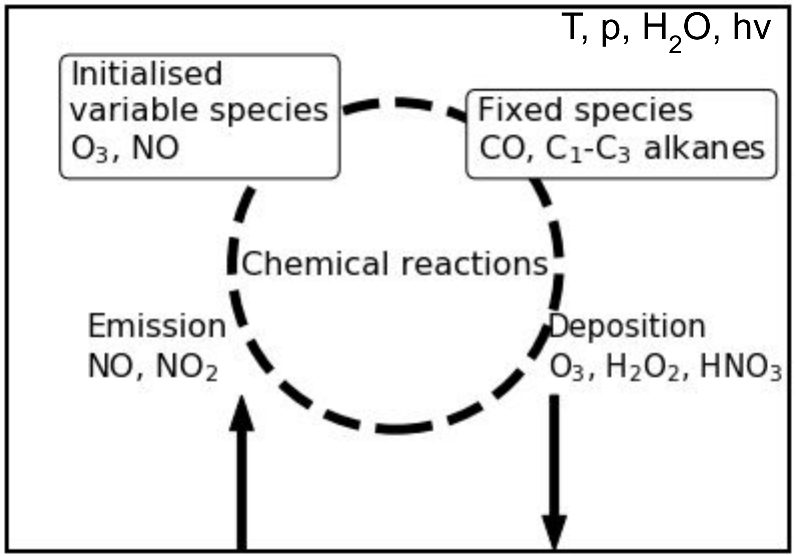
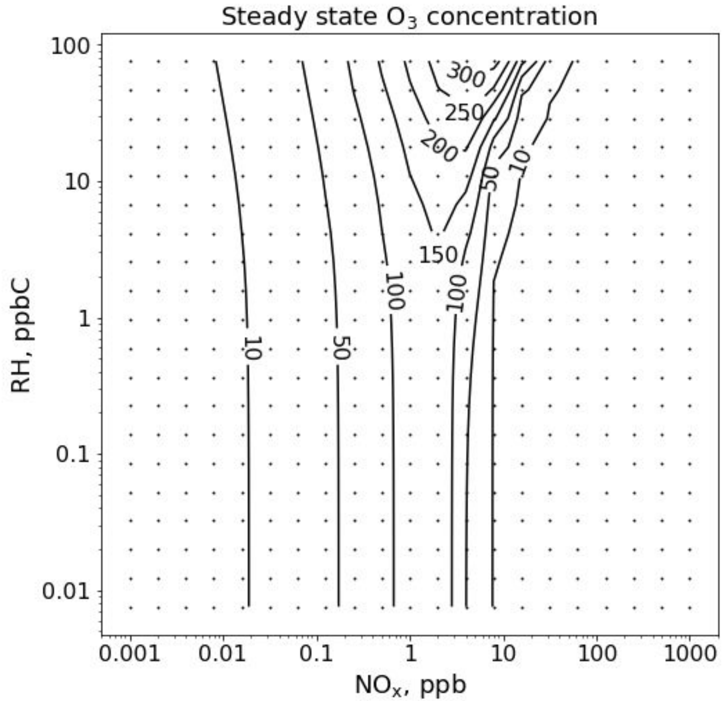
- 21 NO_x × 20 NMHC combinations considered in one experiment

Steady state box model





- To reach steady state, O_3 precursors (NO_x and NMHC) were kept constant
- 21 NO_x × 20 NMHC combinations considered in one experiment
- Chemical mechanisms were compared using isopleths plots of 24 hour average concentrations of various species

Updating chemical kinetics

Benchmark mechanism:
Master Chemical Mechanism (MCM) - a near-explicit chemical mechanism of O_3 generation during VOCs degradation in the boundary layer (Jenkin et al., 1997).

Inorganic + C_1-C_3 RH oxidation requires:

	Species	Reactions
MCM	97	303
CheT	47	120

Updated bimolecular reactions:

1. HO2+EtCO3=O2+EtCO3H
2. **HO2+O3=OH+O2+O2**
3. iPrOO+NO3=Me2CO+HO2+NO2
4. MeOO+MeOO=HO2+HO2+HCHO+HCHO (*)
5. MeOO+MeOO=MeOH+HCHO+O2 (*)
6. NO3+HCHO=HNO3+HO2+CO
7. nPrOO+NO3=EtCHO+HO2+NO2
8. **OH+CH4=H2O+MeOO**
9. **OH+HO2NO2=H2O+NO2+O2**
10. **OH+HONO=H2O+NO2**
11. OH+MeOOH=H2O+MeOO
12. OH+MGLY=MeCO3+CO+H2O
13. OH+OH=H2O+O3P

Updated termolecular reactions:

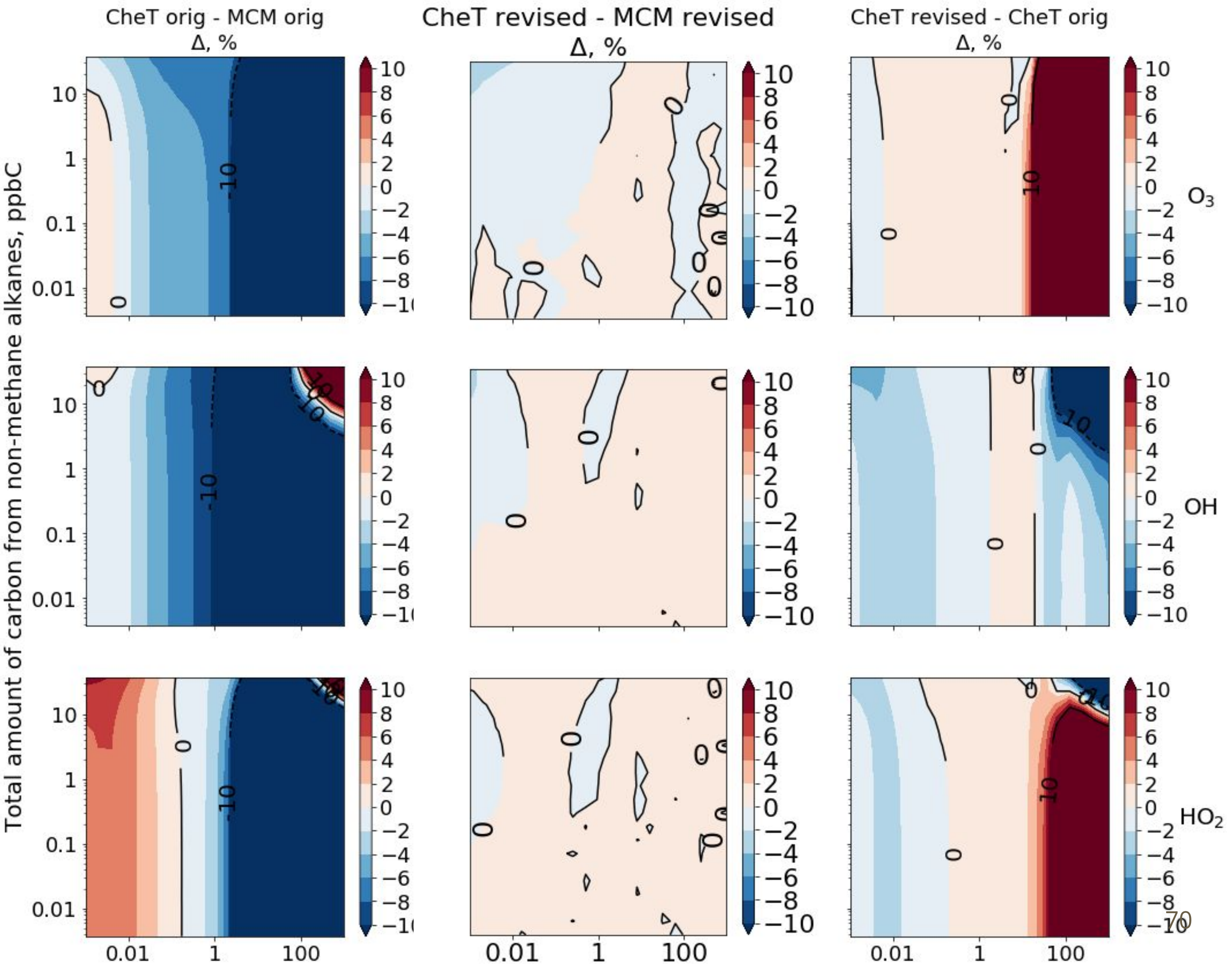
1. **EtCO3+NO2=PPAN+M**
2. **HO2+NO2=HO2NO2+M**
3. **MeCO3+NO2=PAN+M**
4. NO+NO=NO2+NO2 (*)
5. **NO2+NO3=N2O5+M**
6. O+NO=NO2 (*)
7. O+NO2=NO3 (*)

IUPAC vs JPL

(*) box model only

Results: box

- Updating inorganic and C_1-C_3 RH chemistry eliminates the differences in oxidants between mechanisms in a box model
- Updated CheT predicts higher O_3, HO_2 and lower OH at high NO_x but elsewhere it's similar to original



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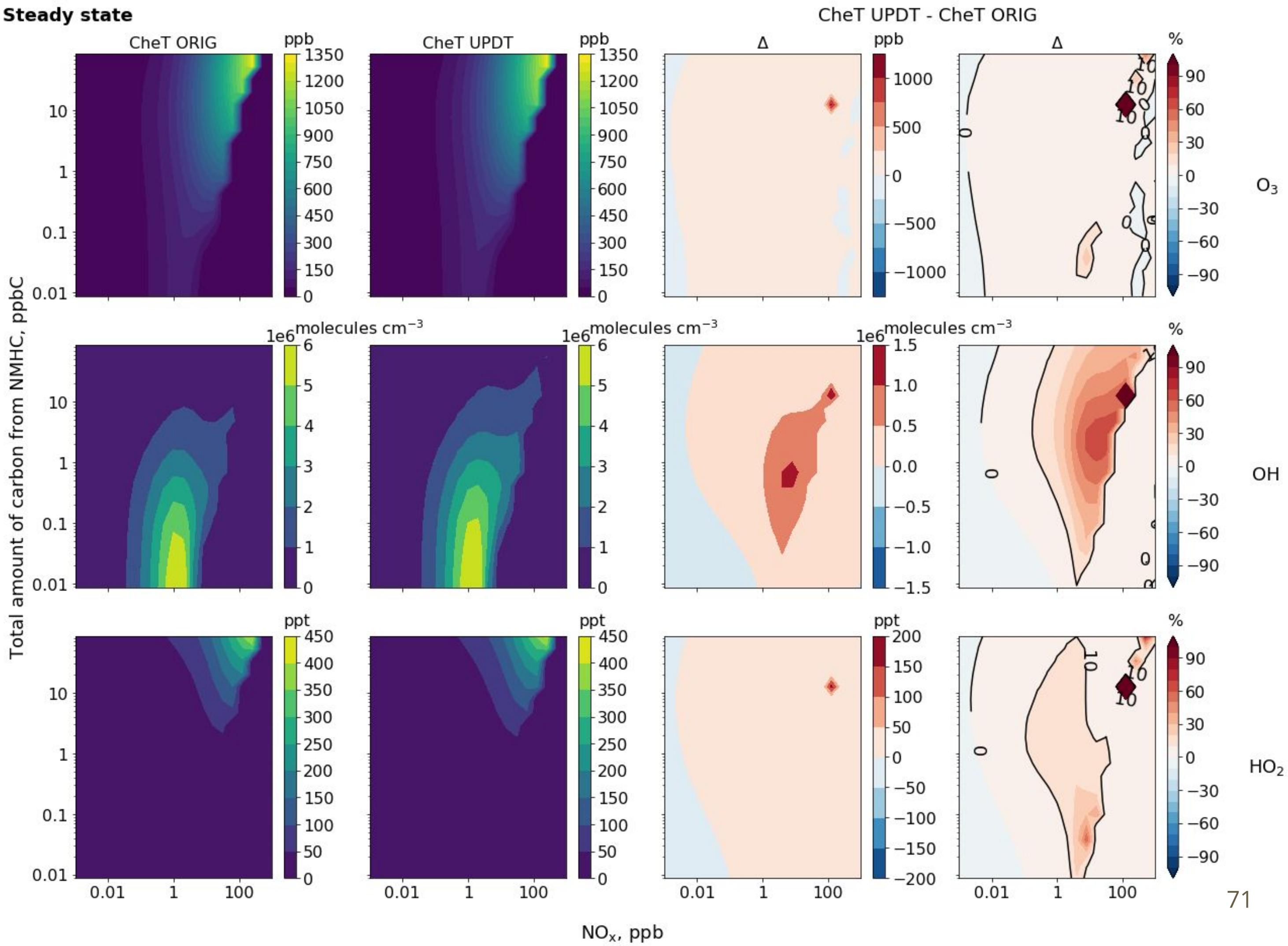


Steady state
CheT UPDT - CheT ORIG
CheT ORIG
CheT UPDT
Δ
ppb
%
molecules cm^{-3}
1e6
ppt
O_3
OH
HO_2
Total amount of carbon from NMHC, ppbC
NO_x, ppb

Versions of $PrONO_2$ chemistry

MCM/CheT_C0C3_revised_AN/base

nPrOO + NO = **nPrONO2** 2.90e-12*exp(350/T)*0.020
iPrOO + NO = **iPrONO2** 2.70e-12*exp(360/T)*0.042
nPrONO2 + OH = EtCHO + NO2 + H2O **5.8e-13**
iPrONO2 + OH = Me2CO + NO2 + H2O **6.20e-13*exp(-230/T)**
nPrONO2 + hv = EtCHO + NO2 + HO2 1.75e-06
iPrONO2 + hv = Me2CO + NO2 + HO2 2.93e-06

- production rates of n- and i-propyl nitrate at 298 K are different by a factor of 2 (nPrONO2 1.88e-13, iPrONO2 3.80e-13)
- iPrONO2 OH oxidation is temperature dependent
- iPrONO2 photolysis is 1.67 times bigger than nPrONO2
- products of n- and i-propyl nitrate oxidation and photolysis are different, with different lifetimes and impacts on the rest of the chemistry
  - Me2CO is longer lived than EtCHO
  - EtCHO -> EtOO -> EtONO2
  - Me2CO -> MeOO -> MeONO2

CheT_C0C3_revised_ANv2

nPrOO + NO = **PrONO2** 2.90e-12*exp(350/T)*0.020
iPrOO + NO = **PrONO2** 2.70e-12*exp(360/T)*0.042
PrONO2 + OH = **Me2CO** + NO2 + H2O **6.20e-13*exp(-230/T)**
PrONO2 + hv = **Me2CO** + NO2 + HO2 **2.93e-06***

*In UKCA: j(MeONO2)

- produce one propyl nitrate instead of two
- branching ratio for iPrOO production from C3H8+OH is 0.736, so iPrOO should be more abundant
- use iPrONO2 OH oxidation and photolysis for lumped PrONO2 chemistry because iPrOO is more abundant

Problems:

- overestimation of PrONO2, Me2CO, MeOO and MeONO2
- underestimation of EtCHO, EtOO and EtONO2

CheT_C0C3_revised_ANv3

nPrOO + NO = **PrONO2** 2.90e-12*exp(350/T)*0.020
iPrOO + NO = **PrONO2** 2.70e-12*exp(360/T)*0.042
PrONO2 + OH = **0.62*EtCHO + 0.38*Me2CO** + NO2 + H2O **5.8e-13**
PrONO2 +hv = **0.4*EtCHO + 0.6*Me2CO** + NO2 + HO2 **2.93e-06***

*In UKCA: j(MeONO2)

- produce one propyl nitrate instead of two
- produce both EtCHO and Me2CO during PrONO2 oxidation and photolysis, with yields derived from the ratio of the corresponding reaction rate coefficients
- use nPrONO2 oxidation and iPrONO2 photolysis rate for PrONO2 as an upper limit

Problems:

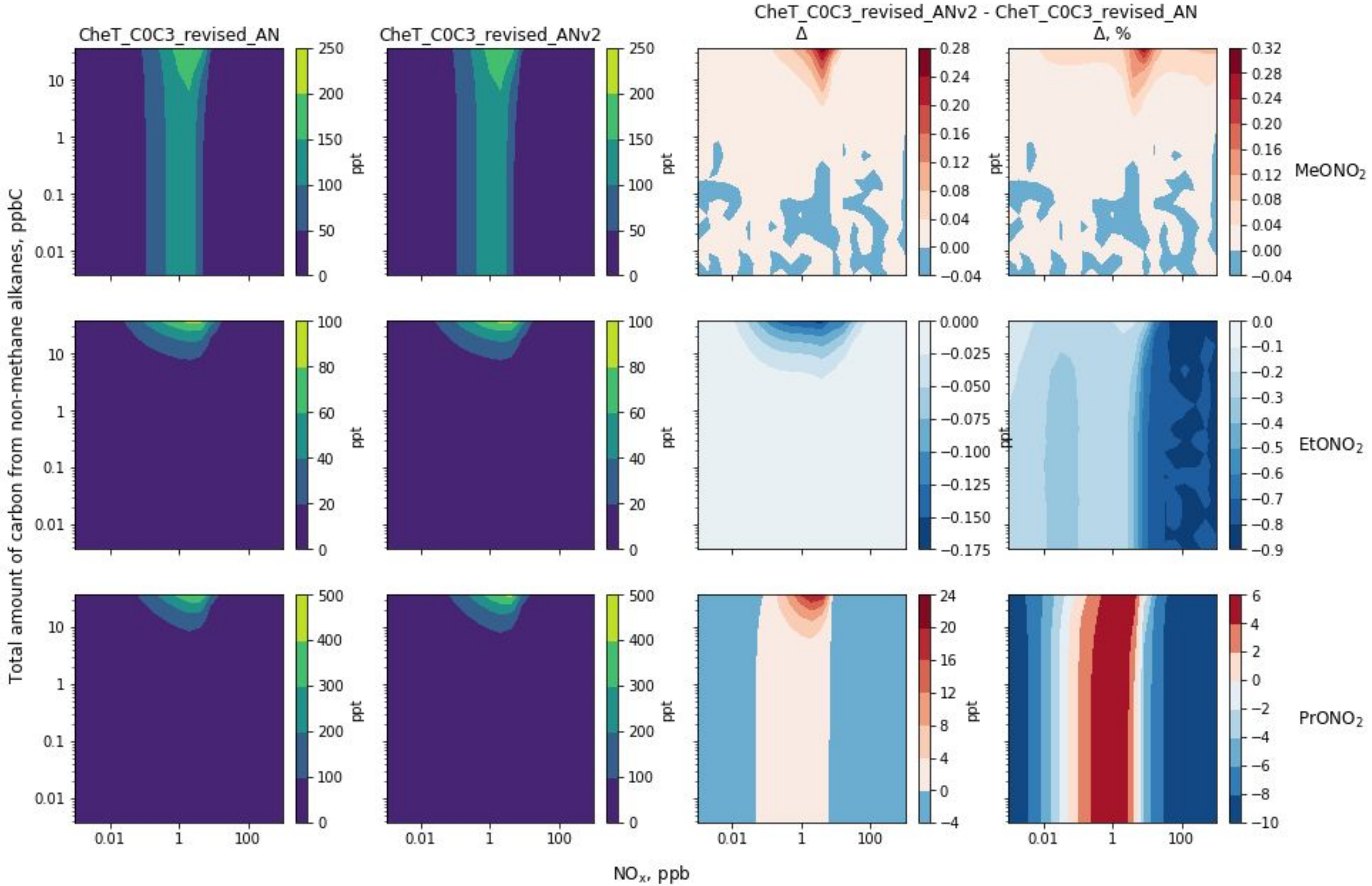
- severe underestimation (up to -160 ppt) of PrONO2 despite it being produced from nPrOO+NO and iPrOO+NO due to high PrONO2+OH/hv rate
- negative bias in O3 (up to -700 ppt)

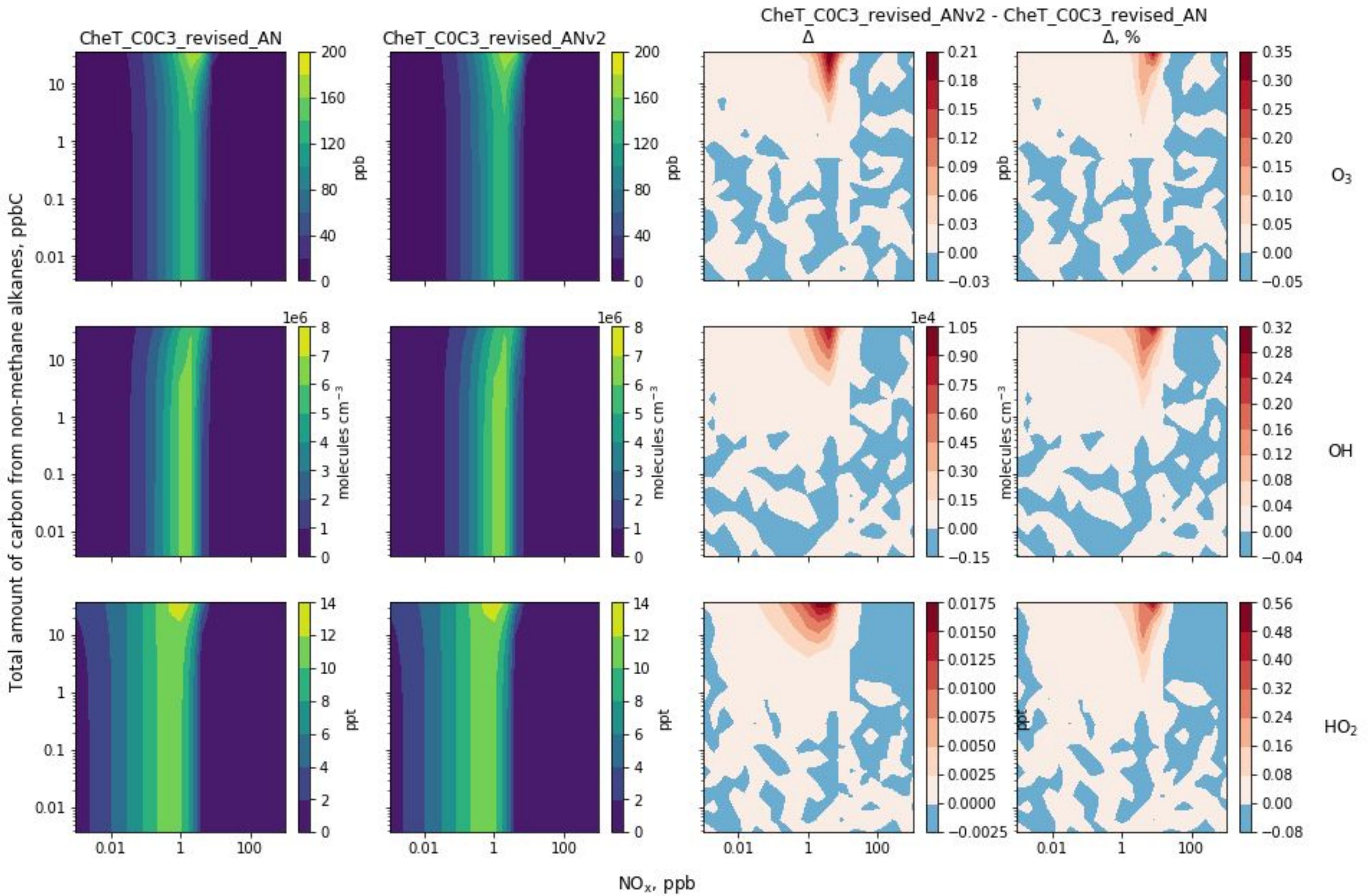
CheT_C0C3_revised_ANv4

nPrOO + NO = **PrONO2** 2.90e-12*exp(350/T)*0.020
iPrOO + NO = **PrONO2** 2.70e-12*exp(360/T)*0.042
PrONO2 + OH = **0.62*EtCHO + 0.38*Me2CO** + NO2 + H2O **(5.8e-13+6.20e-13*exp(-230/T))/2**
PrONO2 +hv = **0.4*EtCHO + 0.6*Me2CO** + NO2 + HO2 **(1.75e-06+2.93e-06)/2***

*In UKCA: j(MeONO2)

- EtONO2, EtCHO, Me2CO and O3 bias is the same as in v3, up to -700 ppt for O3 in O3 production regime (mid NOx-high RH)
- MeONO2, PrONO2 bias is smaller, but to -70 ppt for PrONO2 in O3 production regime (mid NOx-high RH)

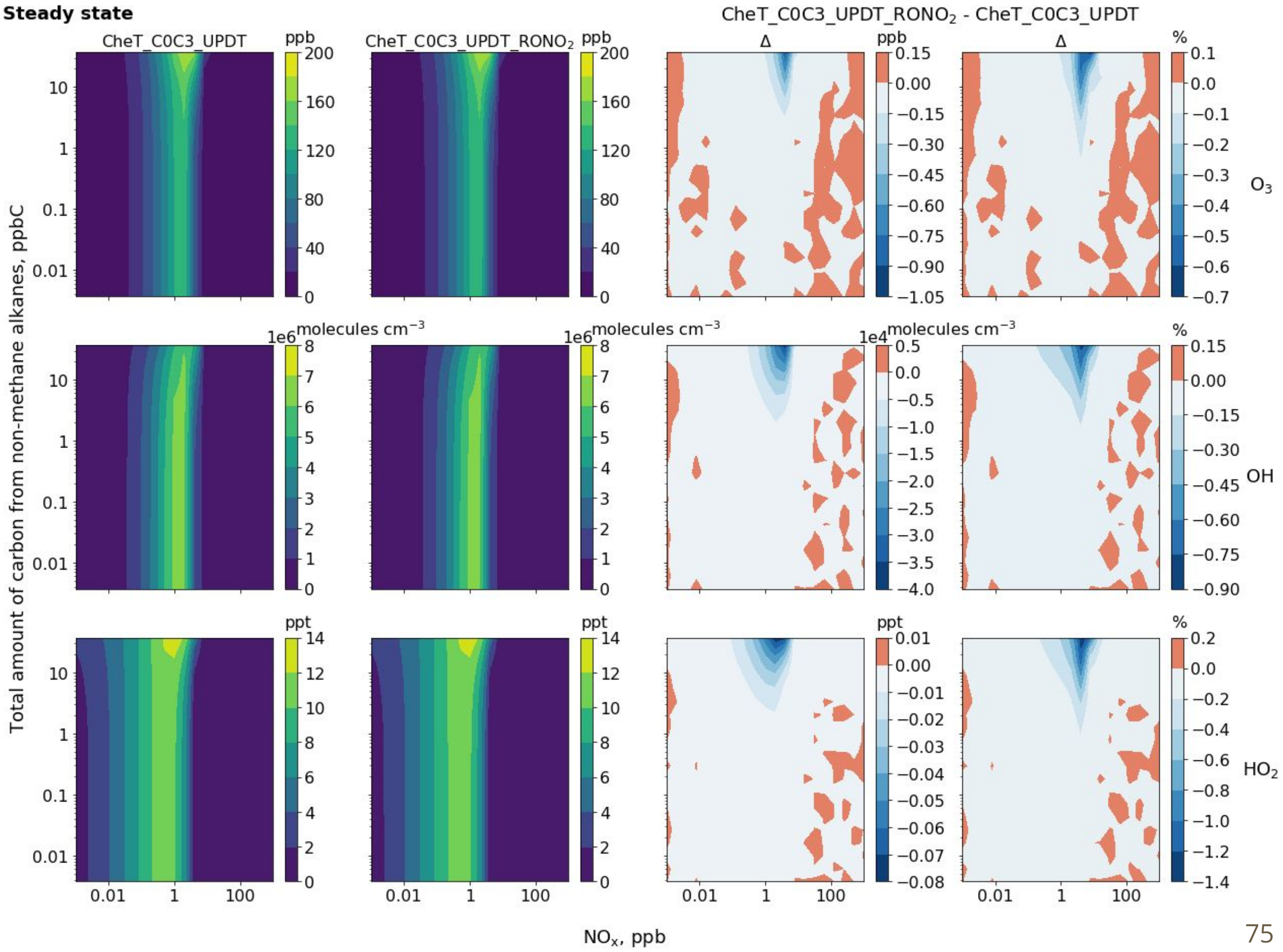

CheT_C0C3_revised_AN
CheT_C0C3_revised_ANv2
CheT_C0C3_revised_ANv2 - CheT_C0C3_revised_AN
Δ
Δ, %
MeONO2
EtONO2
PrONO2
Total amount of carbon from non-methane alkanes, ppbC
NOx, ppb
ppt



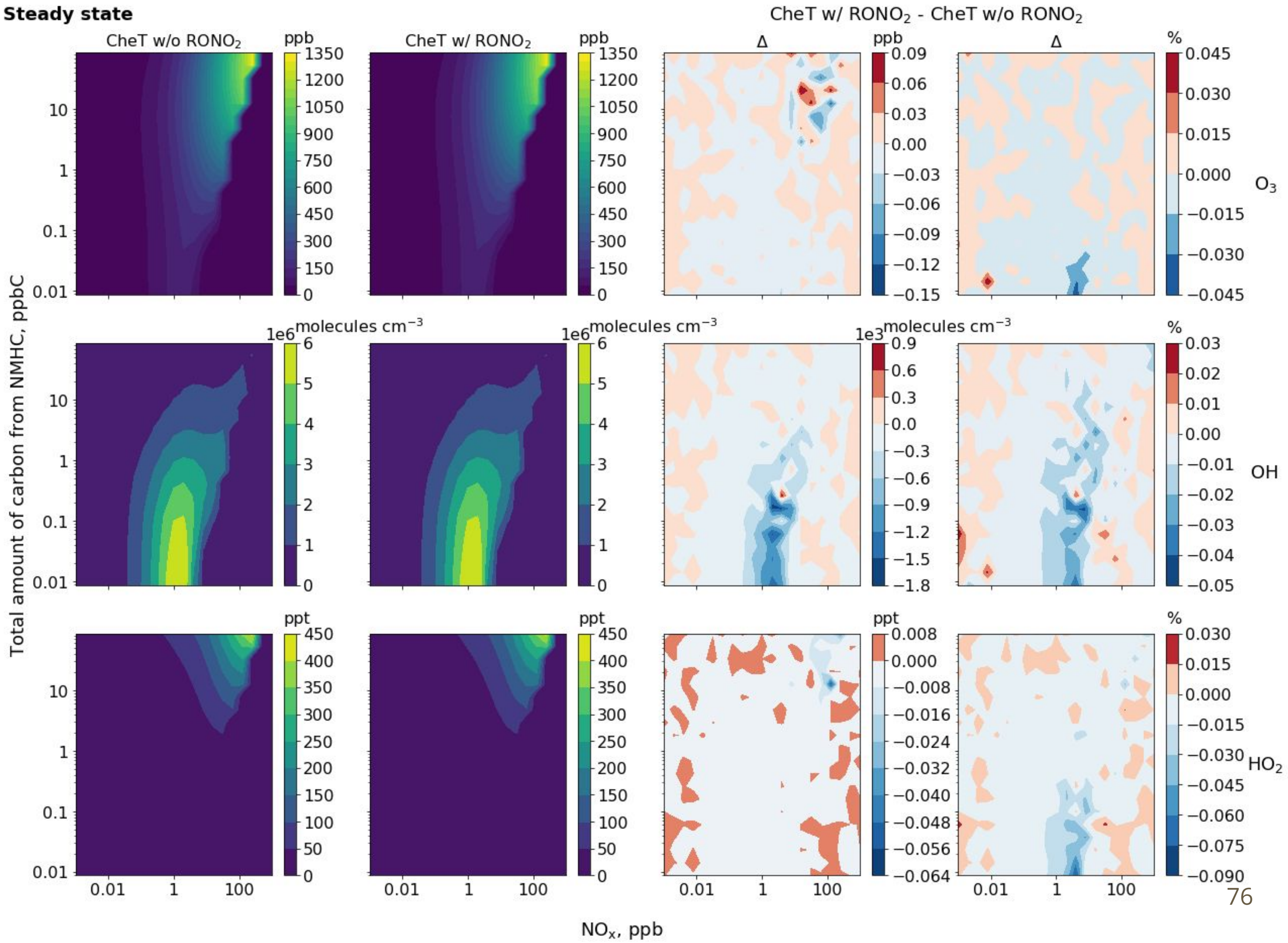
CheT_C0C3_revised_AN
CheT_C0C3_revised_ANv2
CheT_C0C3_revised_ANv2 - CheT_C0C3_revised_AN
Δ
Δ, %
Total amount of carbon from non-methane alkanes, ppbC
NOx, ppb
ppb
molecules cm⁻³
ppt
1e6
1e4
O3
OH
HO2

Results: box

- Addition of C_1-C_3 $RONO_2$ changes steady state O_3, OH and HO_2 by no more than 2%
- At mid NOx-high RH conditions C_1-C_3 $RONO_2$ reduce O3 by ~1 ppb (where baseline O3 is ~180 ppb)



Results: box



Steady state
CheT w/ RONO$_2$ - CheT w/o RONO$_2$
CheT w/o RONO$_2$
CheT w/ RONO$_2$
Δ
Δ
ppb
ppb
ppb
%
O$_3$
molecules cm^{-3}
1e6
1e3
OH
ppt
%
HO$_2$
Total amount of carbon from NMHC, ppbC
NO$_x$, ppb

UKCA experiments

Experiment	Description
BASE	Updated CheST without $MeONO_2$
CHEM	C_1-C_3 $RONO_2$ photochemical production & loss
OCEAN	C_1-C_2 $RONO_2$ oceanic emissions & photochemical loss
BB	C_1-C_3 $RONO_2$ biomass burning emissions & photochemical loss
ALL	C_1-C_3 $RONO_2$ photochemical production & loss + both types of emissions
$RONO_2$ dry deposition switched on in all experiments	

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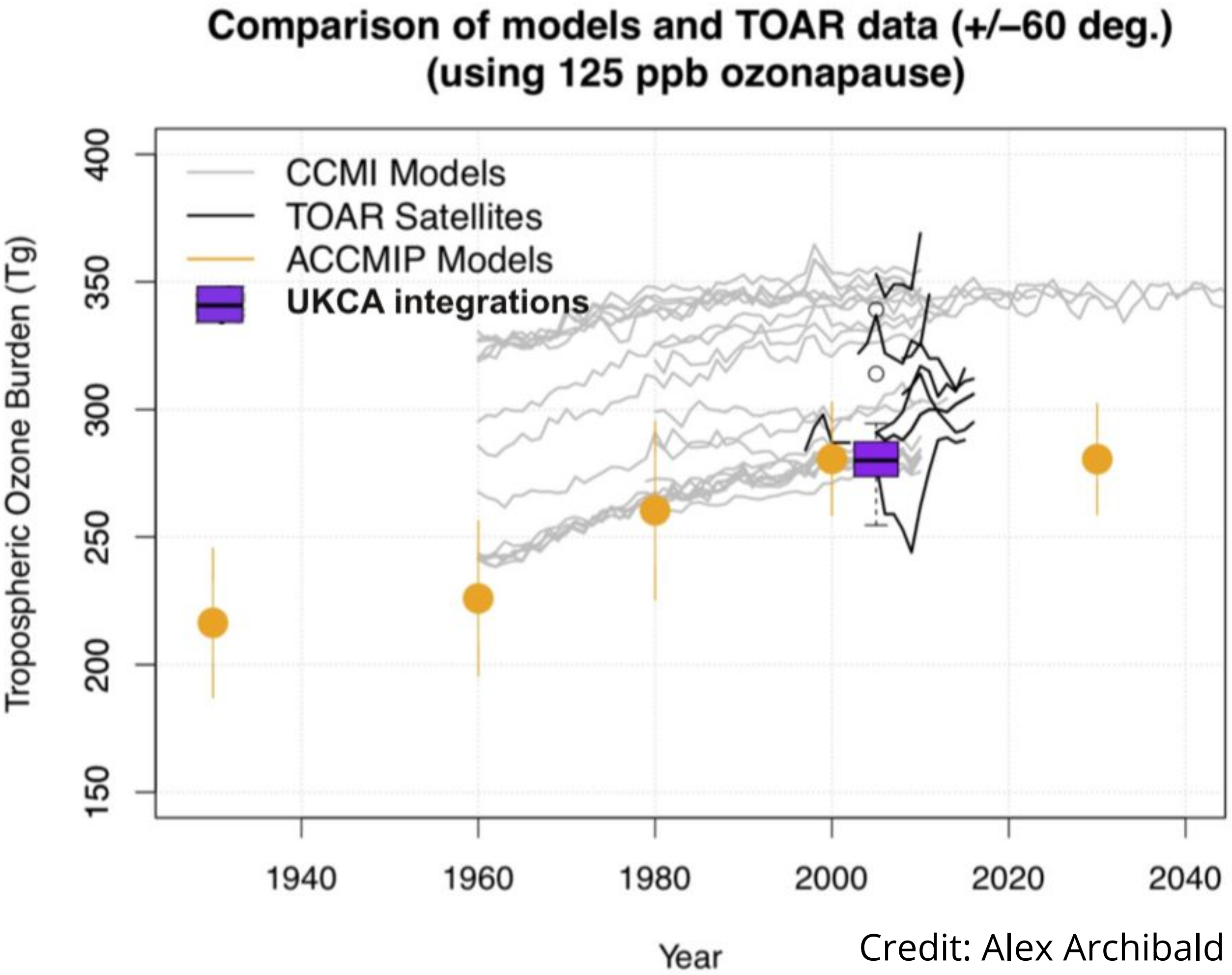
$RONO_2$ dry deposition switched on in all experiments	

Metrics

Name	O3 burden, Tg/yr	CH4 burden, Tg/yr	CH4 lifetime, yr	NH/SH annual OH	MeONO2, Gg/yr	EtONO2, Gg/yr	nPrONO2, Gg/yr
BASE	246.56±2.05	3855.72±91.98	8.68±0.18	1.35±0.02	0.88±2.64	0.00±0.00	0.00±0.00
OCEAN	247.63±1.95	3845.95±86.12	8.59±0.17	1.34±0.02	55.58±1.79	9.49±0.16	0.00±0.00
BB	246.58±1.97	3864.29±93.91	8.68±0.18	1.35±0.02	1.08±2.64	0.11±0.00	0.004±0.000
10-year average 60S60N using chemical troposphere (125 ppb O3) and f(K)*[CH4]*[OH]							

Metrics

Name	O3 burden, Tg/yr	CH Tg	O2,
BASE	246.56±2.05	38	00
OCEAN	247.63±1.95	38	00
BB	246.58±1.97	38	.000
10-year average 60S60N us			



Credit: Alex Archibald

Statistical tests

1. Shapiro-Wilk test for normality.
2. if data is normally distributed:
   a. Paired samples t-test

   else:

   b. Wilcoxon signed-rank test
3. Control false discovery rate to better interpret multiple hypothesis tests.

$RONO_2$ emission factors from biomass burning

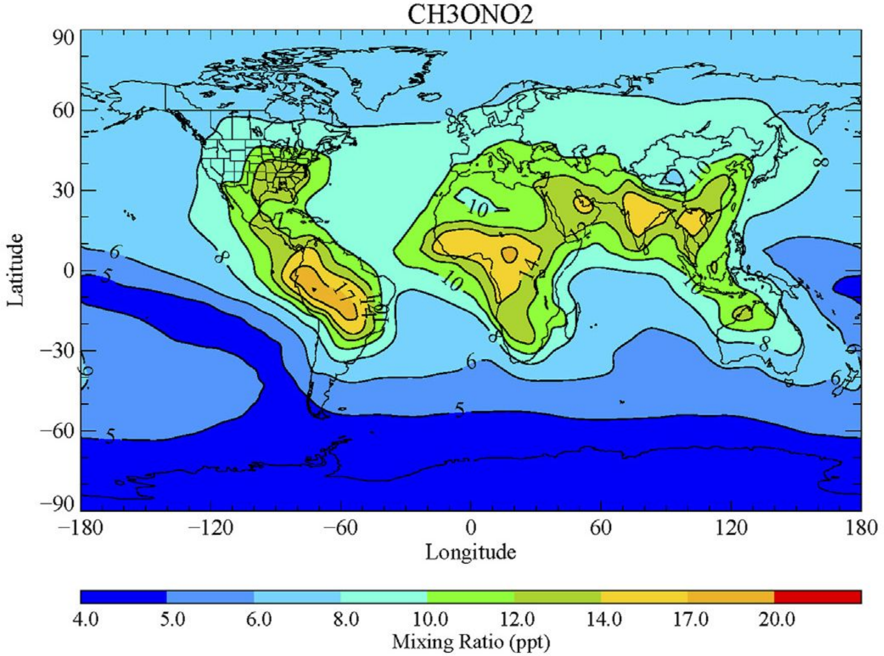
$RONO_2$	tropical forest	savanna	crop residue	pasture maintenance	boreal forest	temperate forest	extratropical forest
$MeONO_2$	8.29×10^{-3} (1.60×10^{-2})	5.1×10^{-4} (3.7×10^{-4})	-	-	2.83×10^{-3}	-	2.83×10^{-3}
$EtONO_2$	5.70×10^{-3}	3.51×10^{-4}*	-	-	1.78×10^{-3}	-	1.78×10^{-3}
$nPrONO_2$	3.00×10^{-4}	1.85×10^{-5}*	-	-	3.23×10^{-4}	-	3.23×10^{-4}
$iPrONO_2$	3.00×10^{-4}	6.15×10^{-5}*	-	-	3.23×10^{-3}	-	3.23×10^{-3}
From Akagi et al. (2011) Table 1. *calculated in this work							

$RONO_2$ burdens

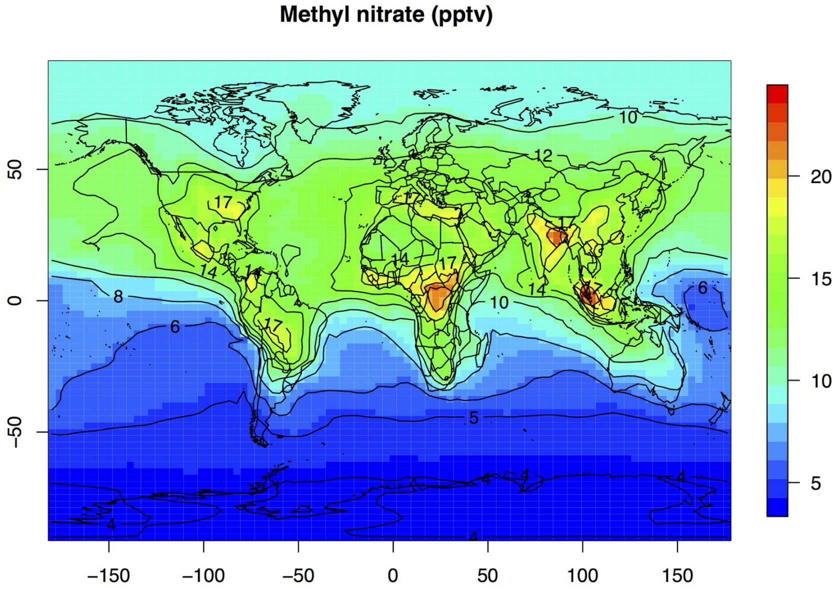
$RONO_2$ burden, Gg N	OCEAN	BB
Neu et al. (2008)	28.7 $MeONO_2$ 6.3 $EtONO_2$	-
Williams et al. (2014)	0.3 ORGNIT	-
Khan et al. (2015)	-	1.1 $MeONO_2$ 0.4 $EtONO_2$ 0.02 $nPrONO_2$ 0.08 $iPrONO_2$
this study*	66.16 MeONO2 11.47 EtONO2	1.21 MeONO2 0.11 EtONO2 0.004 nPrONO2

*10-year average using 125 ppb ozonopause

Primary results: methyl nitrate from CHEM run

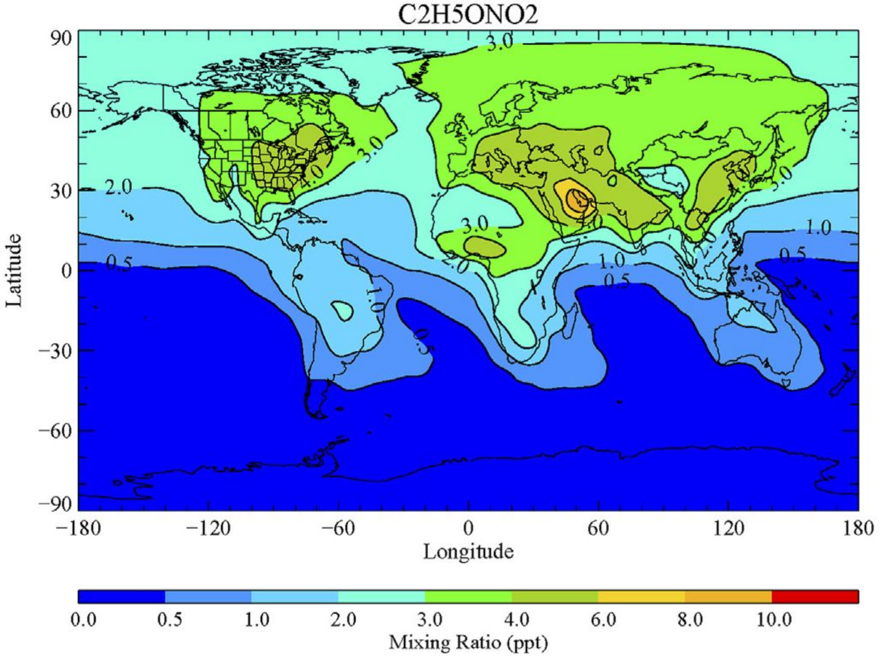


Credit: Khan et al. (2015)

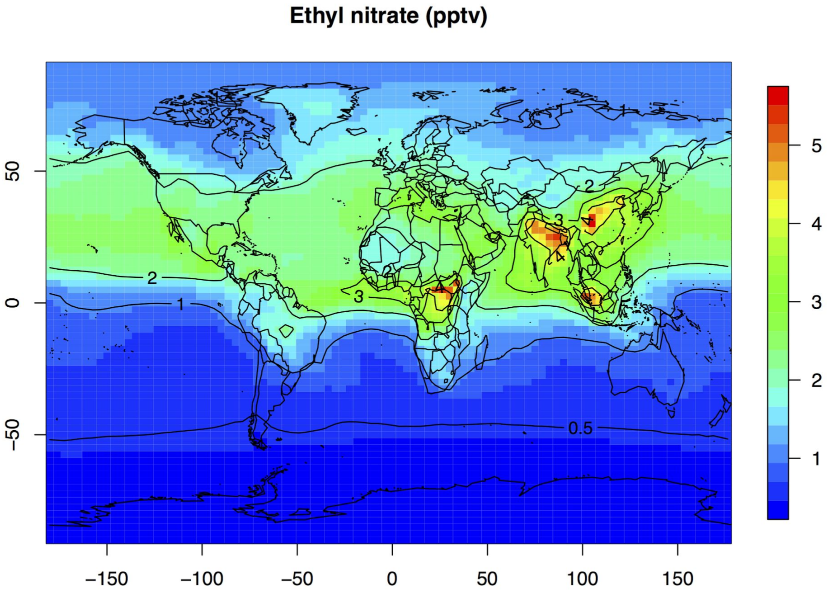


Credit: Paul Griffiths

Primary results: ethyl nitrate from CHEM run

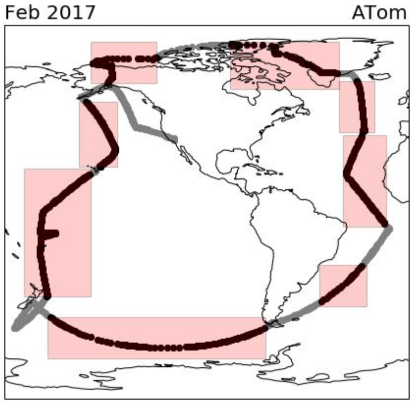


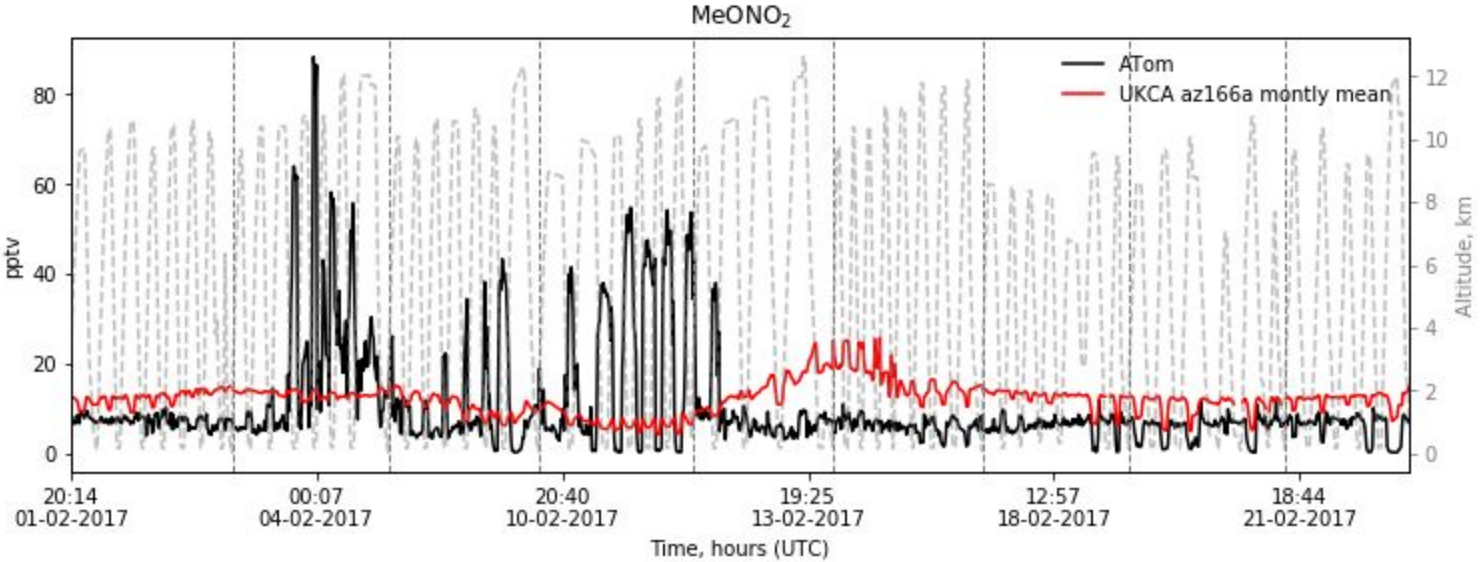
Credit: Khan et al. (2015)



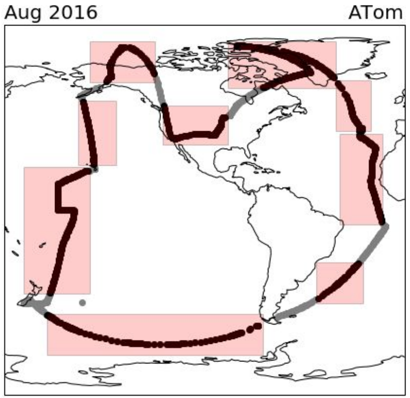
Credit: Paul Griffiths

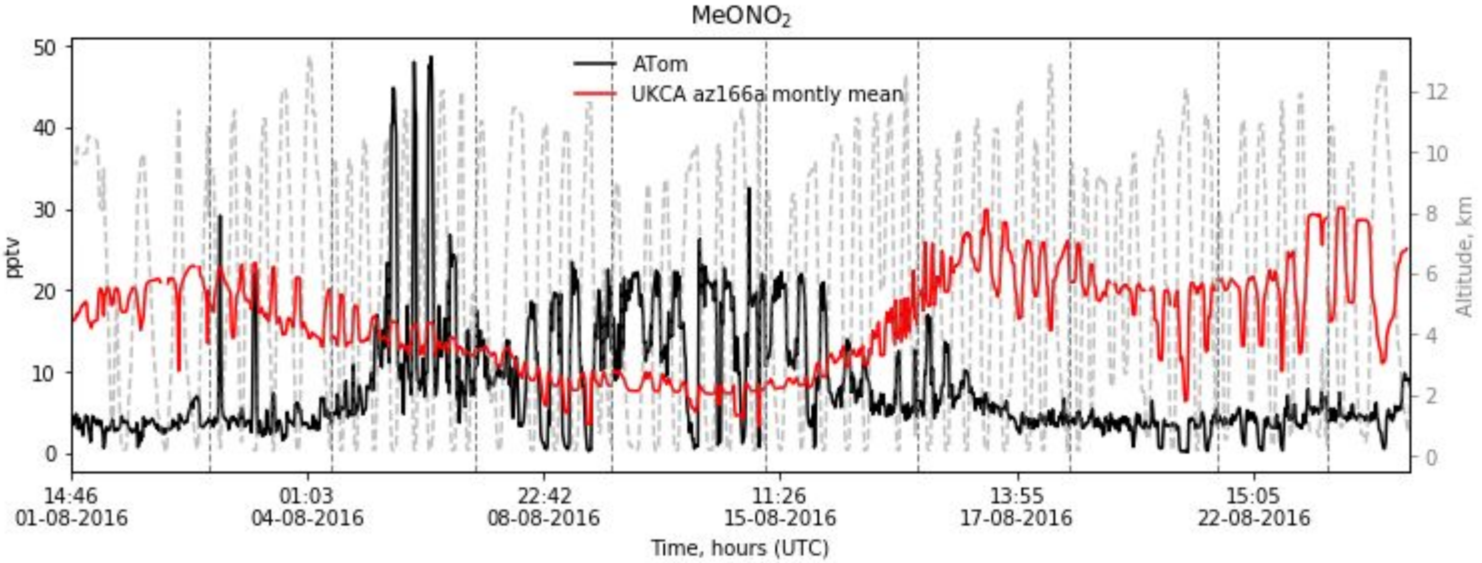
Validation


Feb 2017
ATom


MeONO$_2$
ATom
UKCA az166a montly mean
pptv
Altitude, km
0
20
40
60
80
0
2
4
6
8
10
12
20:14 01-02-2017
00:07 04-02-2017
20:40 10-02-2017
19:25 13-02-2017
12:57 18-02-2017
18:44 21-02-2017
Time, hours (UTC)

Validation


Aug 2016
ATom


MeONO2
ATom
UKCA az166a montly mean
pptv
Altitude, km
0
10
20
30
40
50
0
2
4
6
8
10
12
14:46
01-08-2016
01:03
04-08-2016
22:42
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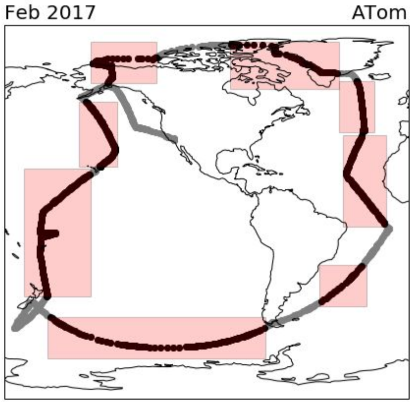
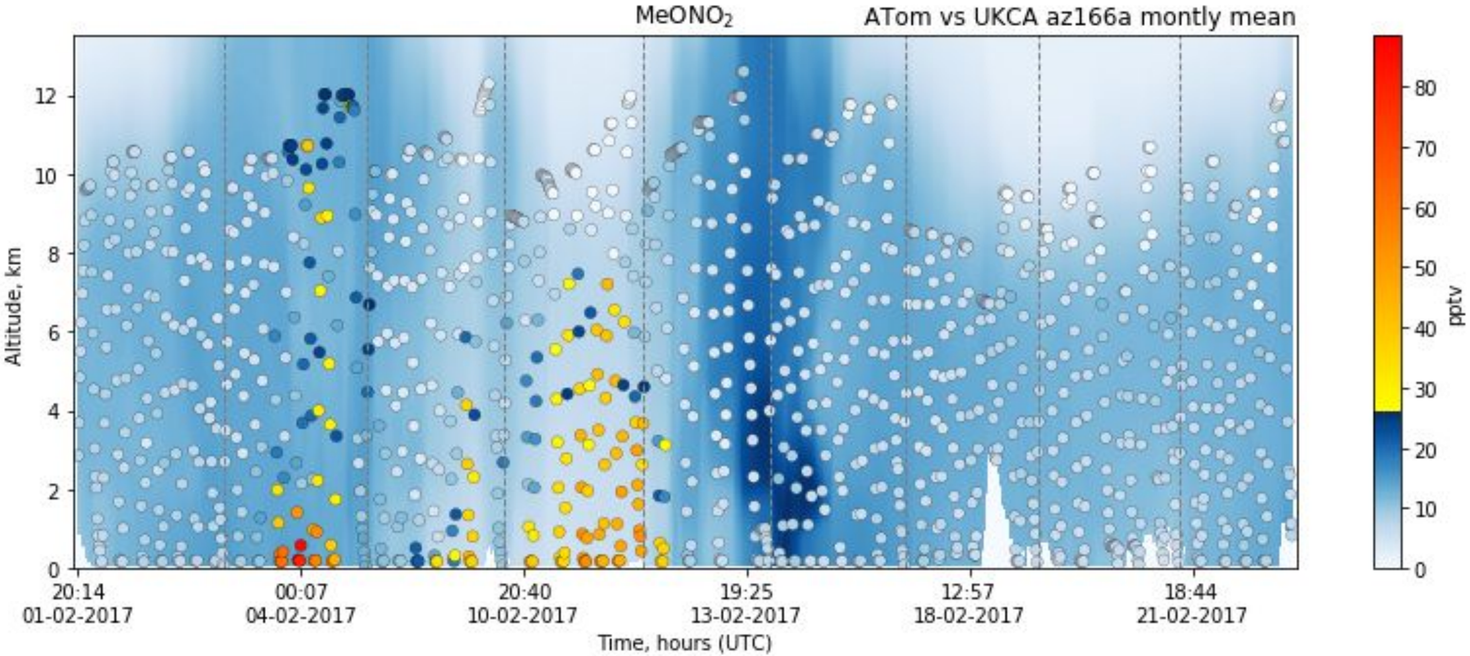
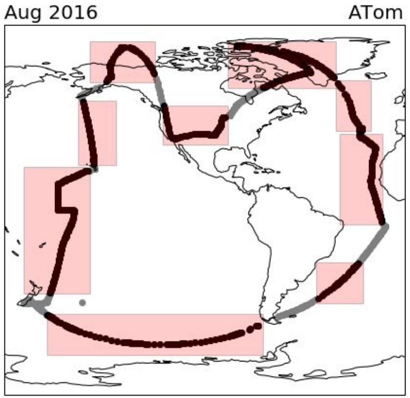
15:05
22-08-2016
Time, hours (UTC)

Validation

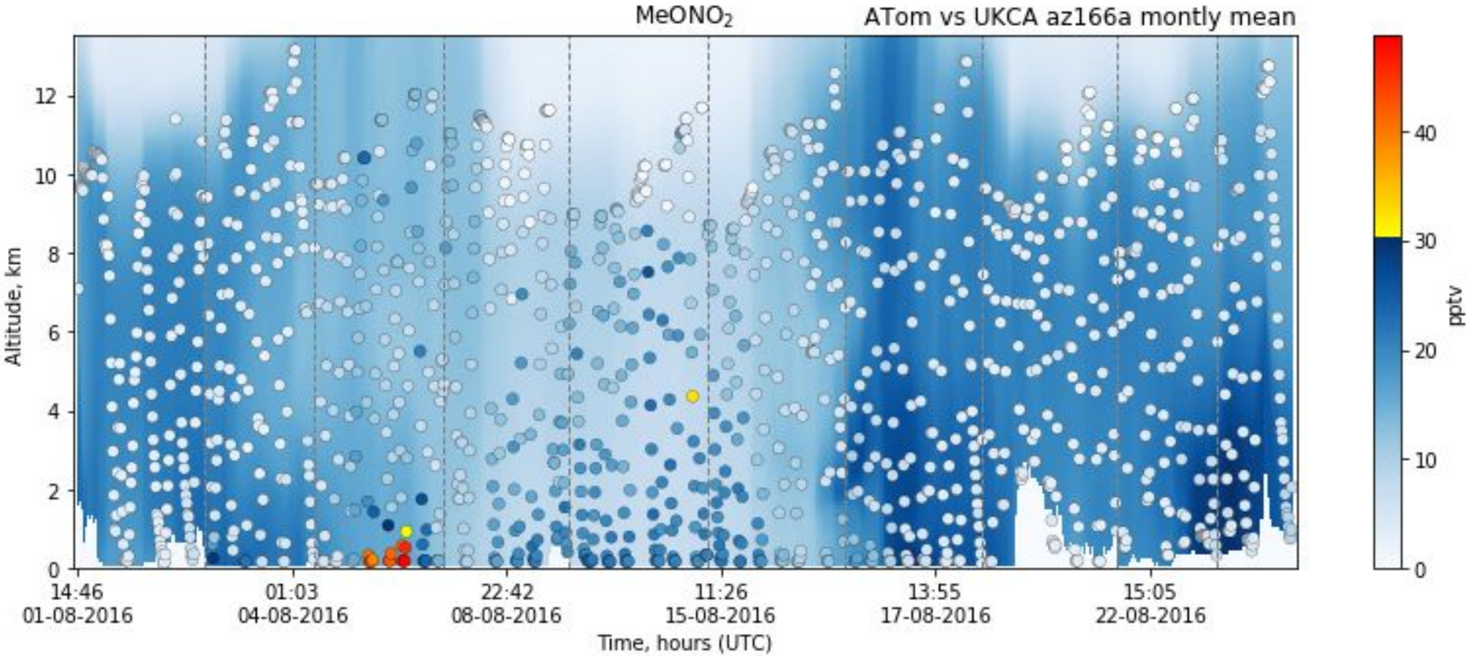

Feb 2017
ATom


MeONO$_2$
ATom vs UKCA az166a montly mean
Altitude, km
0
2
4
6
8
10
12
20:14 01-02-2017
00:07 04-02-2017
20:40 10-02-2017
19:25 13-02-2017
12:57 18-02-2017
18:44 21-02-2017
Time, hours (UTC)
pptv
0
10
20
30
40
50
60
70
80

Validation



Aug 2016
ATom



MeONO$_2$
ATom vs UKCA az166a montly mean
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0
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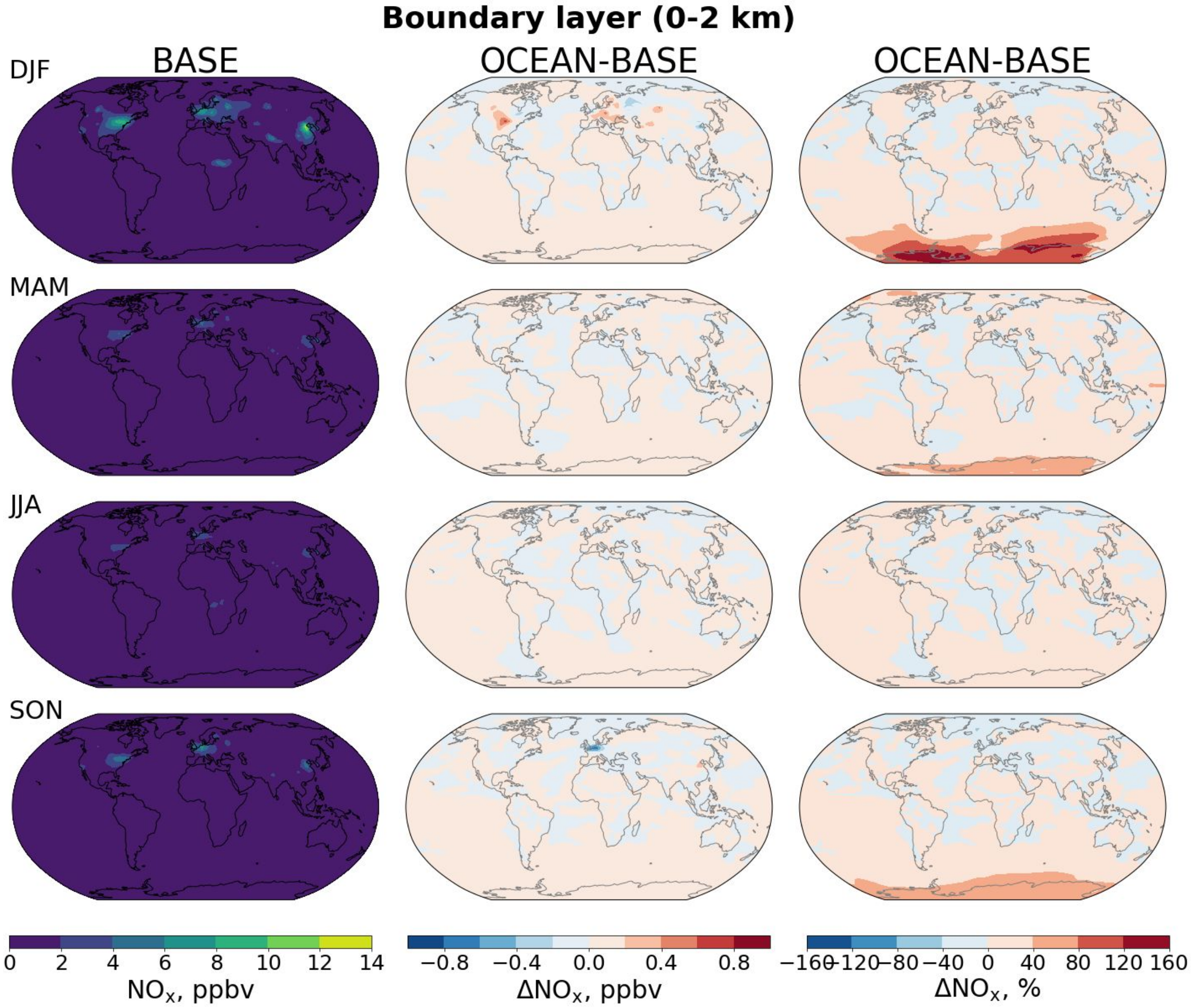
01-08-2016
01:03
04-08-2016
22:42
08-08-2016
11:26
15-08-2016
13:55
17-08-2016
15:05
22-08-2016
Time, hours (UTC)
pptv
0
10
20
30
40

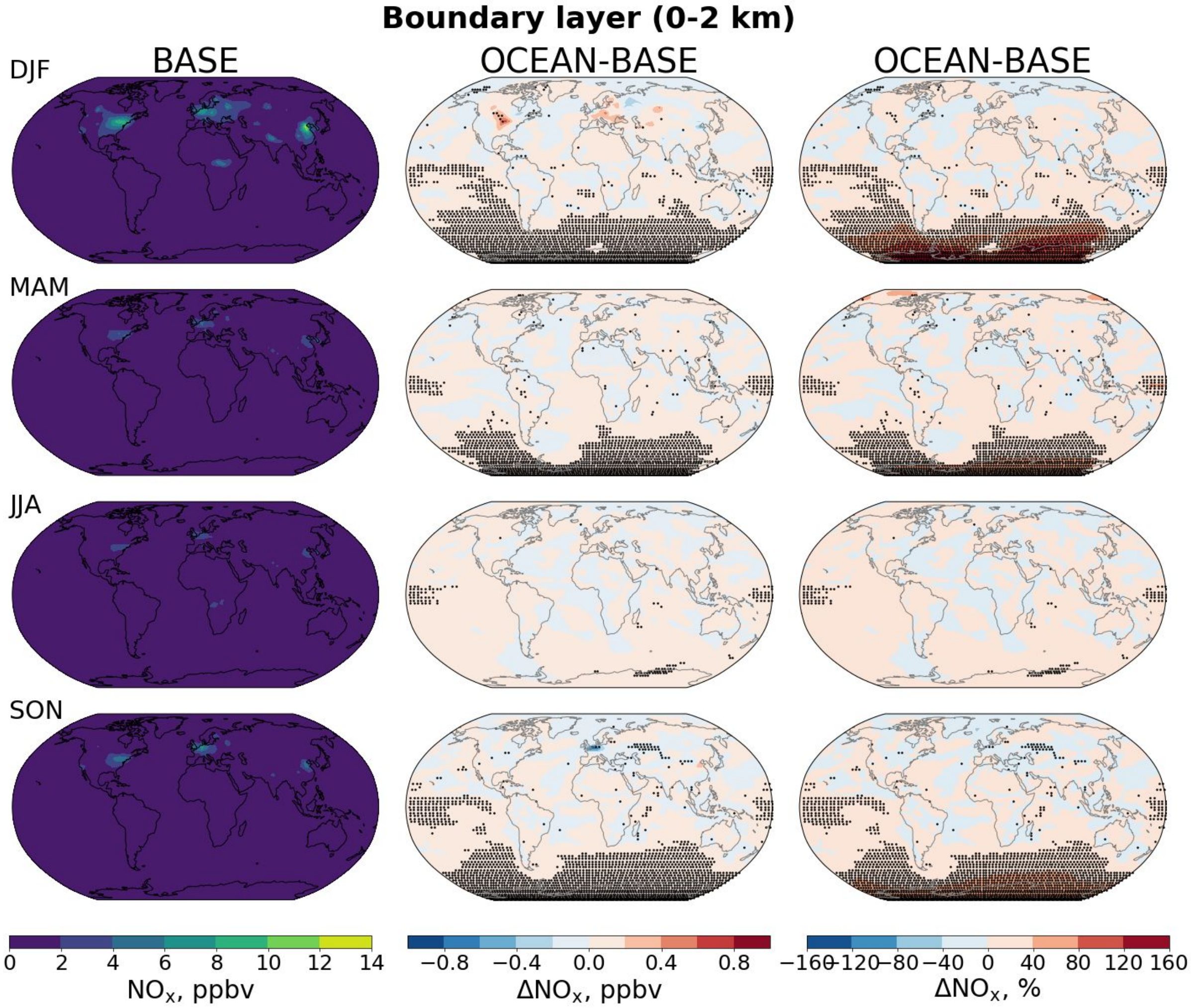
Impact of oceanic $RONO_2$ on NO_x

- increase over the Southern Ocean by up to 160% (< 700 ppt)



Impact of oceanic $RONO_2$ on NO_x

- increase over the Southern Ocean by up to 160% (< 700 ppt)
- statistically significant in all seasons except JJA



Impact of BB $RONO_2$ on NO_x

- increase over the equatorial Africa by up to 80% (< 800 ppt)
- statistically significant in DJF and SON