Nuclear War In a World Brimming With Plastic: Impacts of Cl, Br, and Organics on the Ozone Layer

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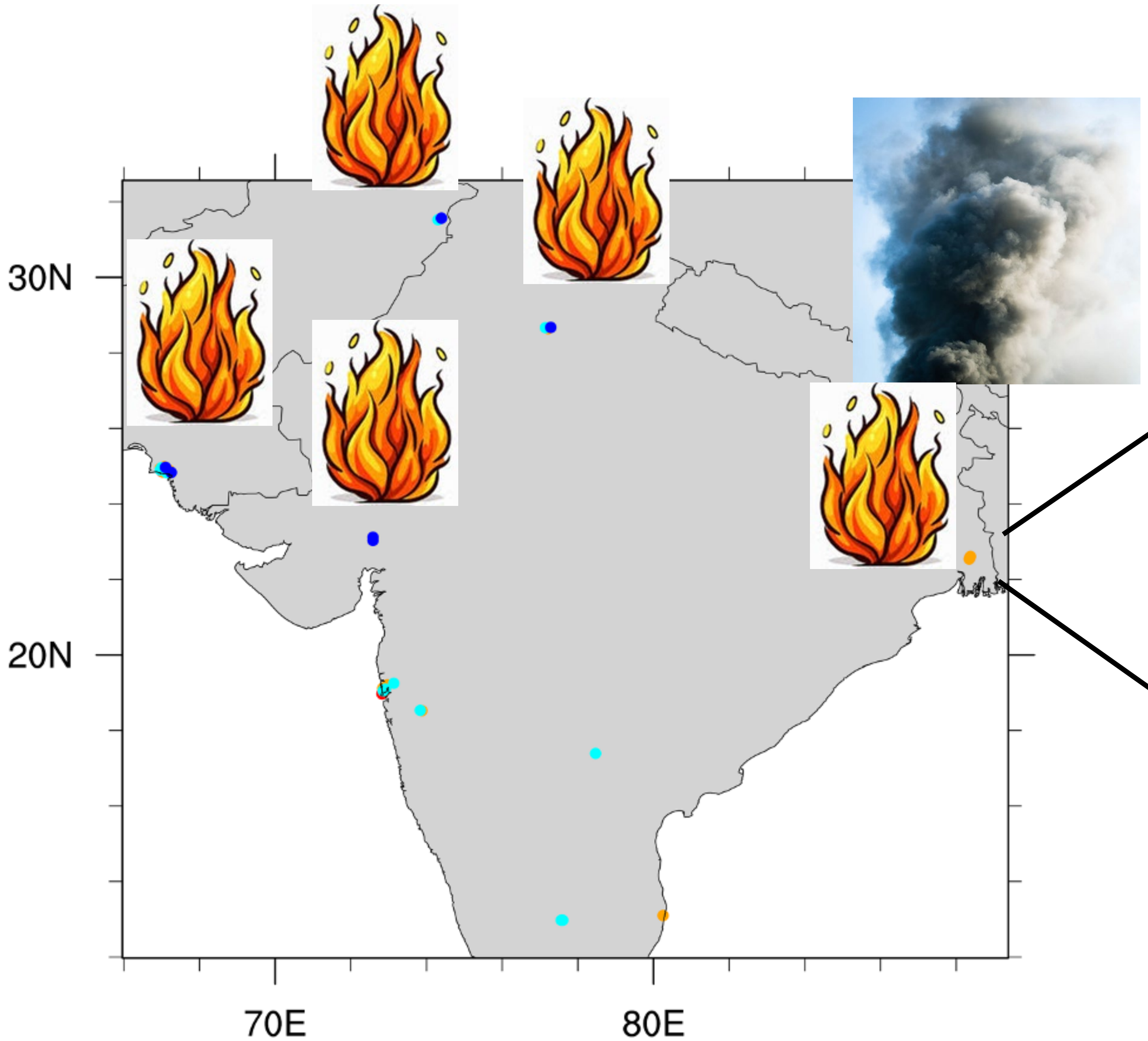
CESM Workshop

June 11, 2025

“Regional Conflicts” using Smaller Scale Nuclear Weapons

India Pakistan Conflicts



Mills et al. (2007; 2014), Toon et al. (2019), Bardeen et al. (2021)

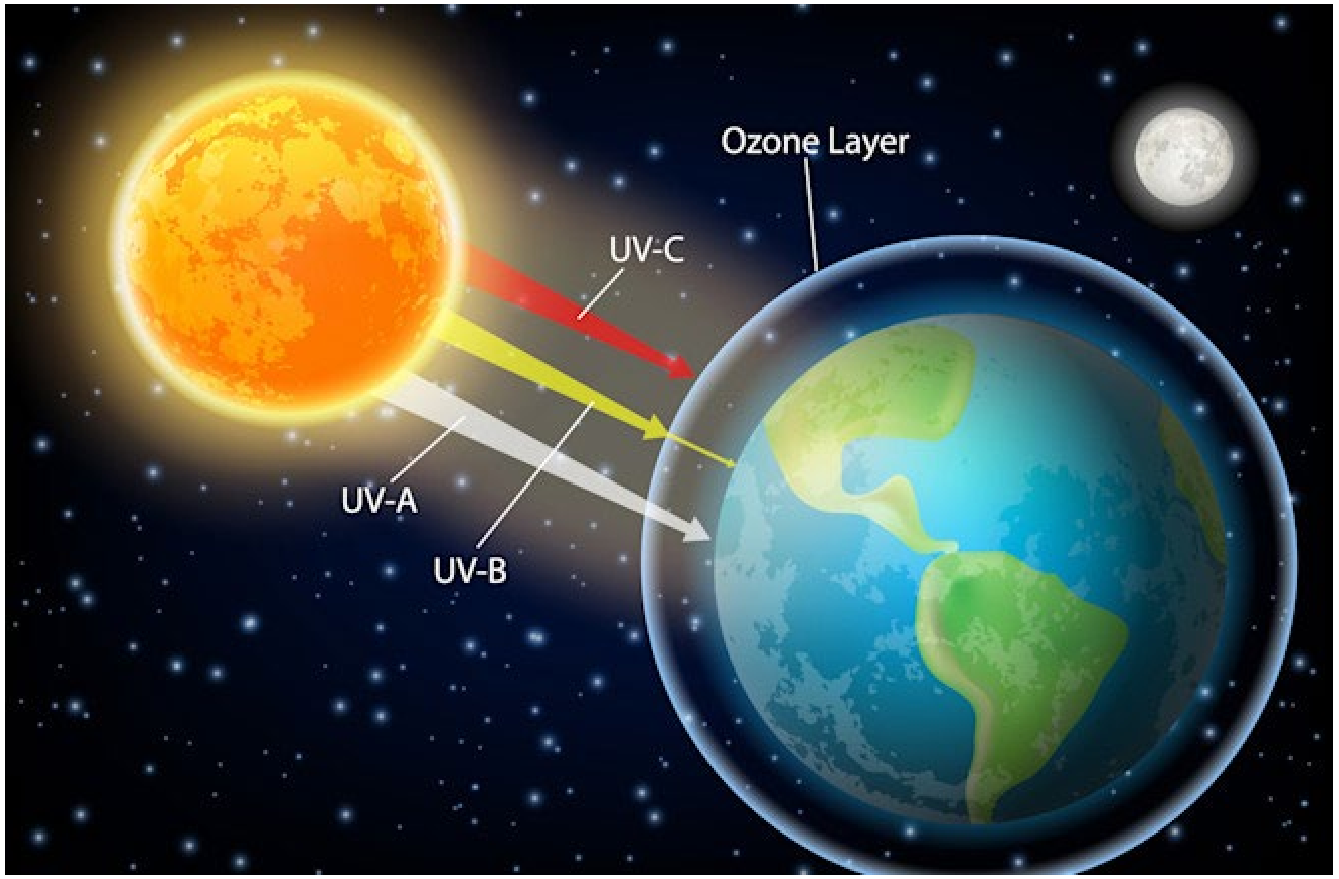
New study:
70:30 ratio for BC/OC

~5 Tg of smoke injection into the atmosphere

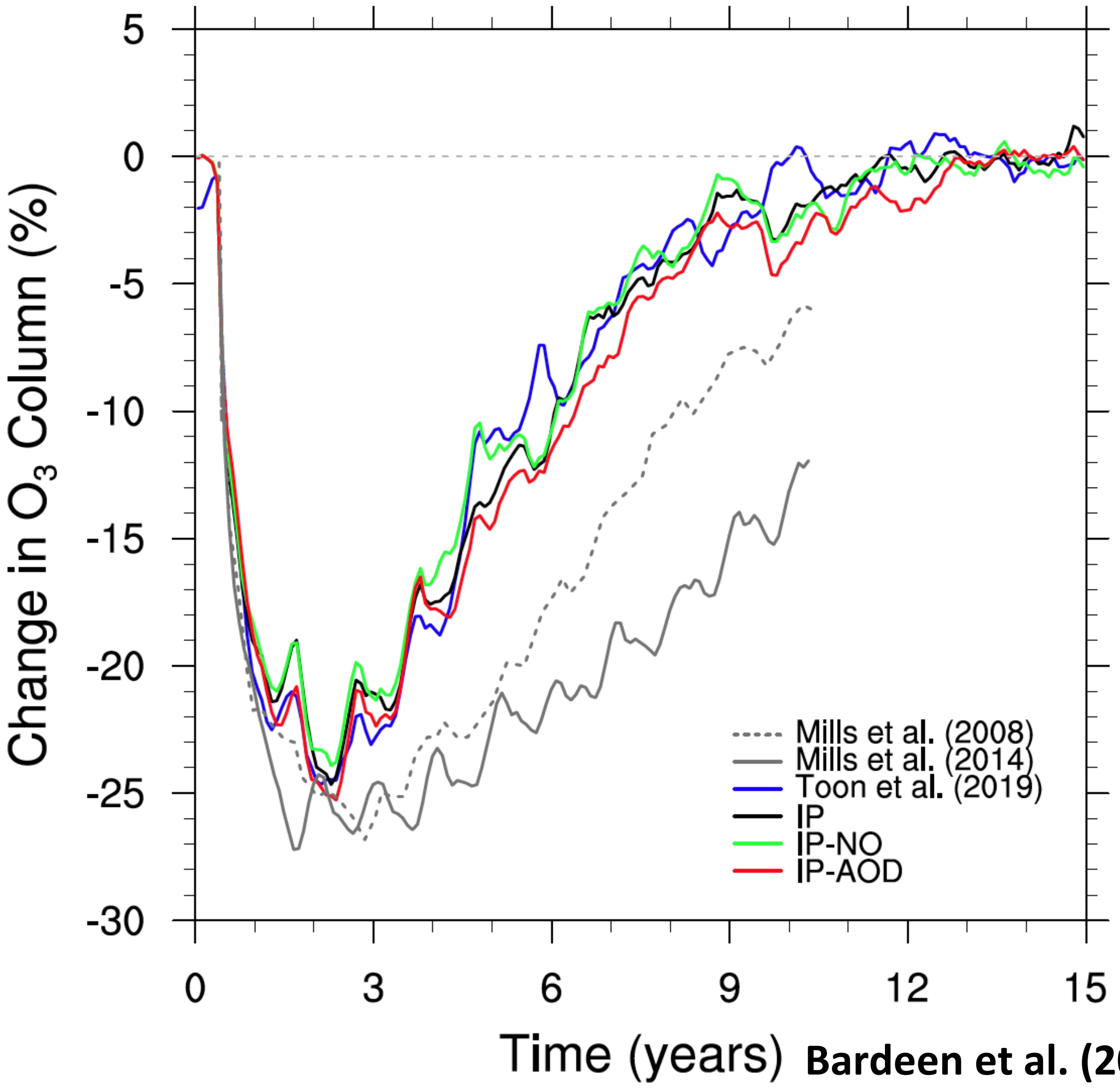
large-scale urban fires

Stratospheric Ozone Layer

Ozone layer



Change in global ozone burden from the 5 Tg soot injection (India-Pakistan) cases



Bardeen et al. (2021)

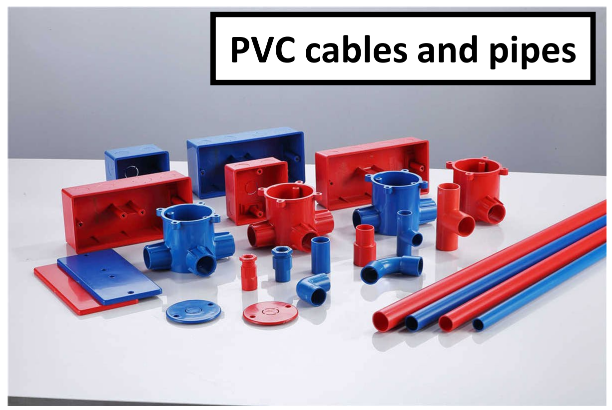
~5 Tg of smoke injection into the stratosphere → $\Delta T > 0$ → $\Delta O_3 \simeq -\Delta k_i[O_3](T) < 0$

Halogen Content in Urban Structures and Industrial Products

Chlorine


Domestic

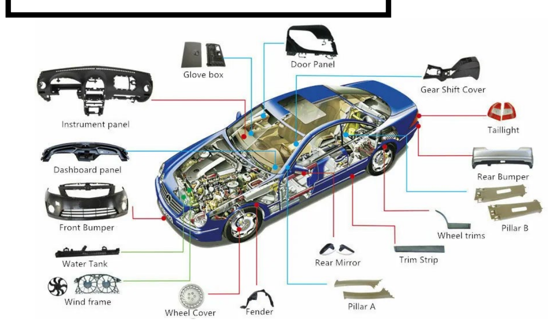
Chlorine is an ingredient in bleach, cleaning products, and antifreeze.


PVC cables and pipes

Leisure


Windows

Vinyl packaging


Automotive


Bromine


Flame retardant

Dye


Medical


Domestic/Clea ning


https://www.bpf.co.uk/plastipedia/polymers/PVC.asp x

https://www.compoundchem.com/019/06/12/iypt035-bromine/

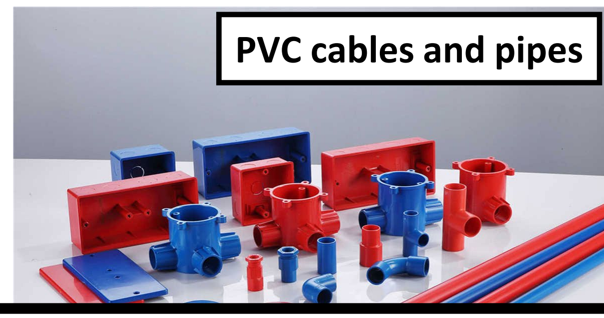
Halogen Content in Urban Structures and Industrial Products

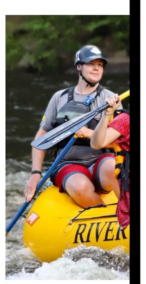
Chlorine

Domestic

Chlorine is an ingredient in bl

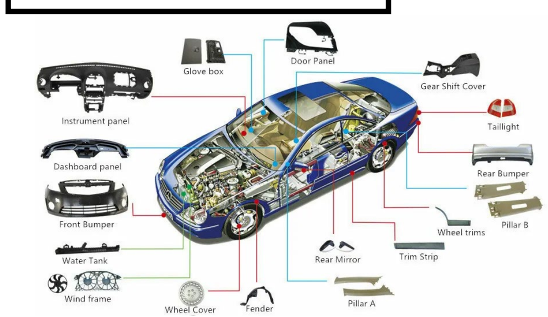
PVC cables and pipes





Vinyl packaging

Automotive



Bromine

Dye

/Clea

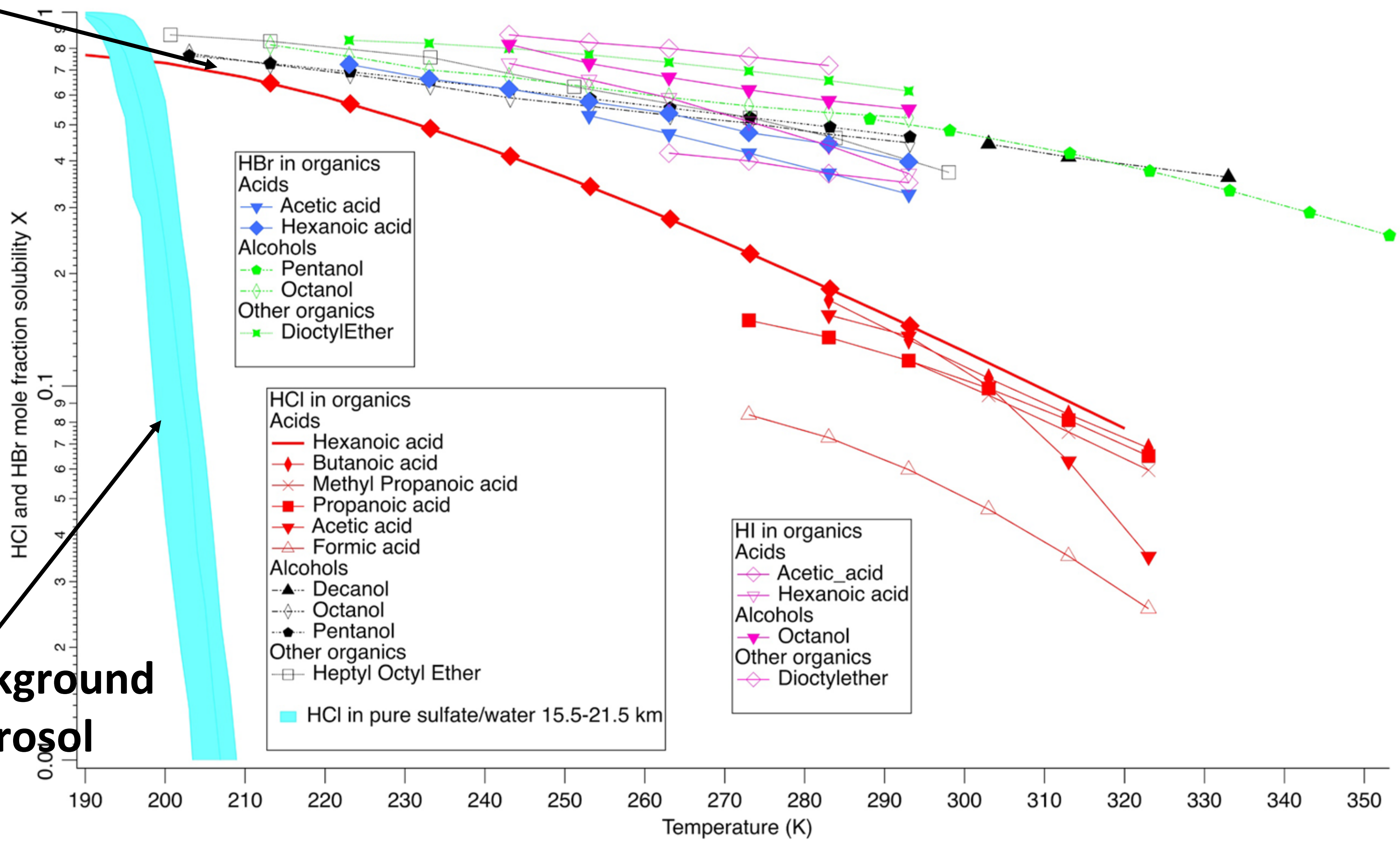
Atmospheric halogens are key ozone-depleting substances

https://www.bpf.co.uk/plastipedia/polymers/PVC.aspx

https://www.compoundchem.com/019/06/12/iypt035-bromine/

HCl, HBr, and HI solubility in different aerosol surface

Organic aerosol



volcanic/background sulfate aerosol

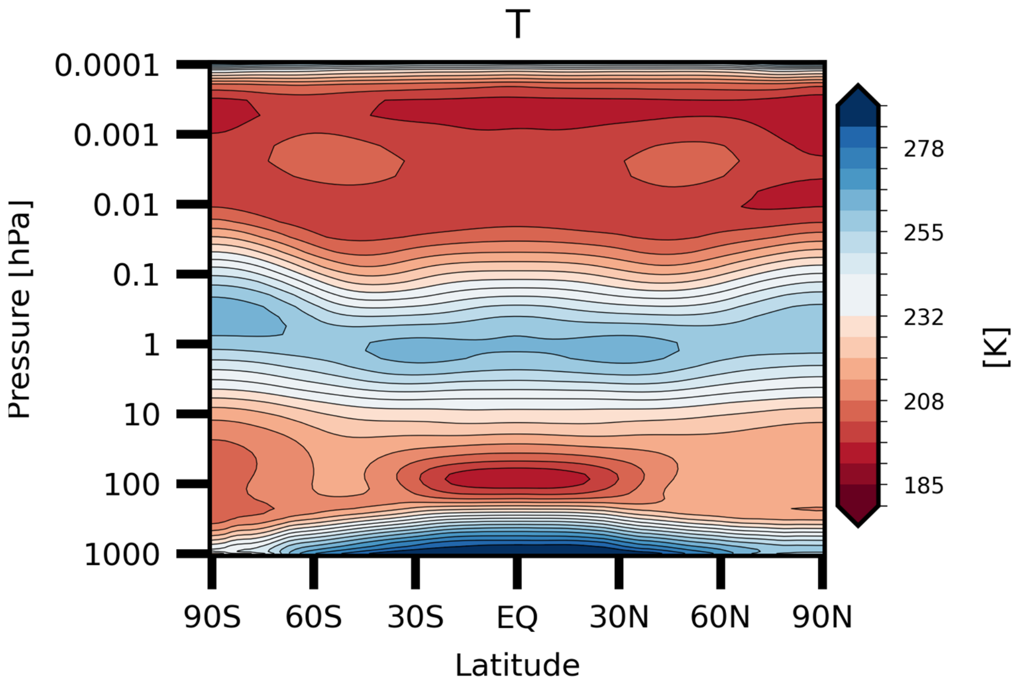
Typical range of stratospheric temperatures

From Solomon et al. (2023)

Model Descriptions

Whole Atmosphere Community Climate Model Version 4 (WACCM4) with Community Aerosol and Radiation Model for Atmospheres (CARMA)

- Includes detailed ozone chemistry: Ox, NOx, HOx, ClOx, BrOx, and heterogeneous reactions on sulfate aerosols
- Updates on HCl solubility on organic carbons
- Injection of 5Tg of BC, 1.6 Tg of OC, 0.5 Tg of NO, 3Tg of Cl, 0.08 Tg of Br

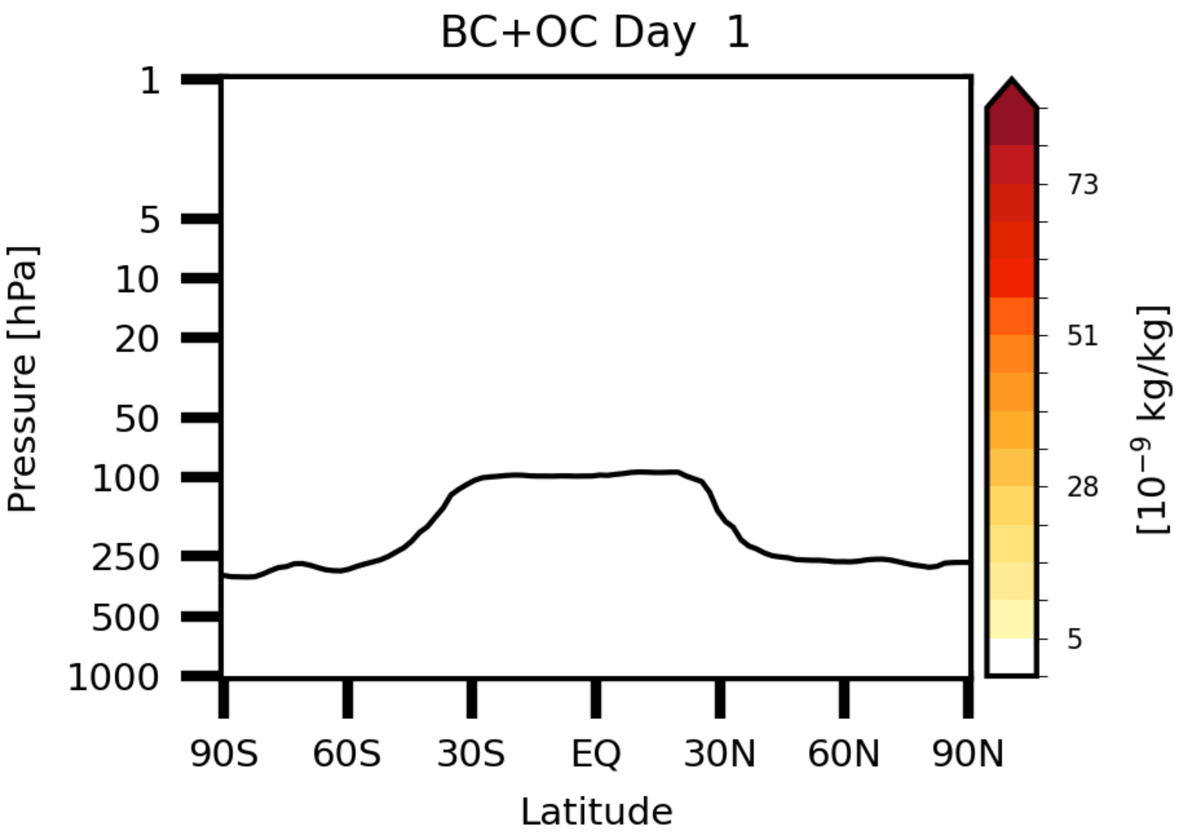


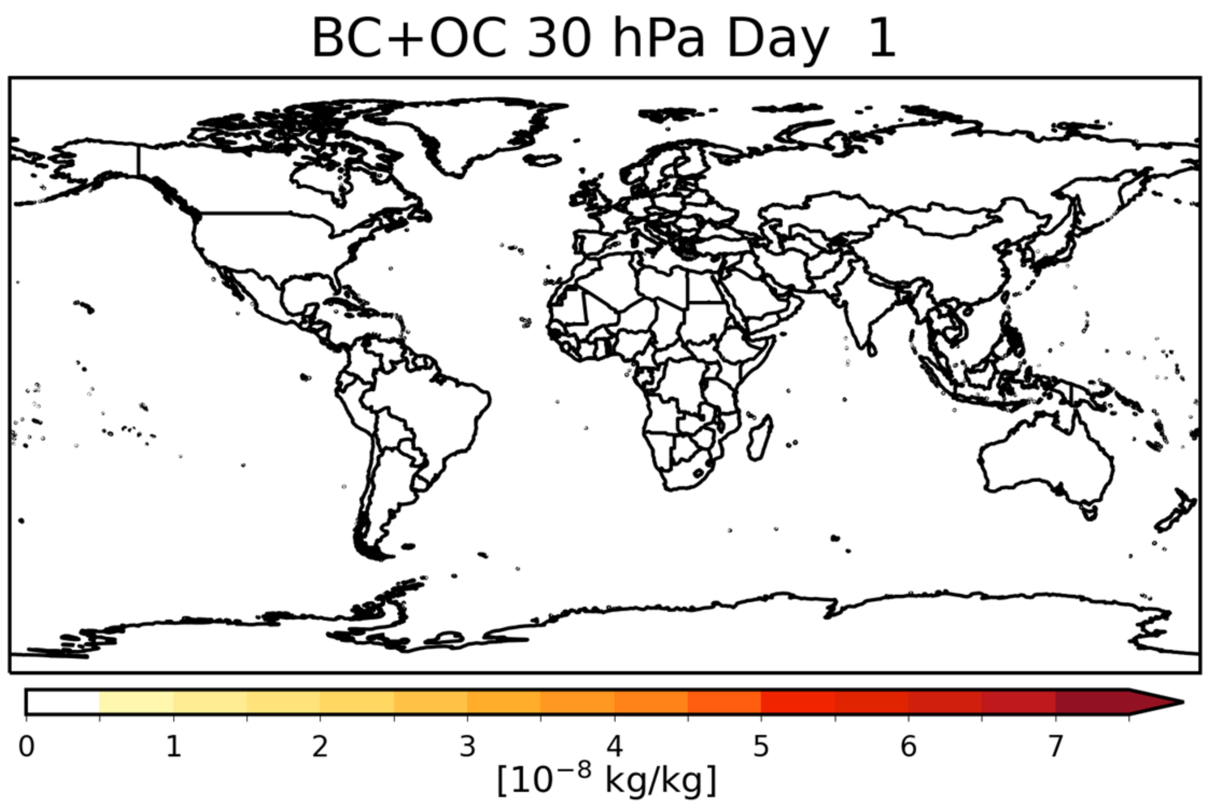
List of Experiments

Experiments \ Emissions	BC/OC	Cl	Br	NO
Control	-	-	-	-
BC/OC	X	-	-	-
BC/OC+Cl/Br/NO	X	X	X	X
BC/OC+Cl	X	X	-	-
BC/OC+Br	X	-	X	-
BC/OC+NO	X	-	-	X

Evolution of Smoke Plume

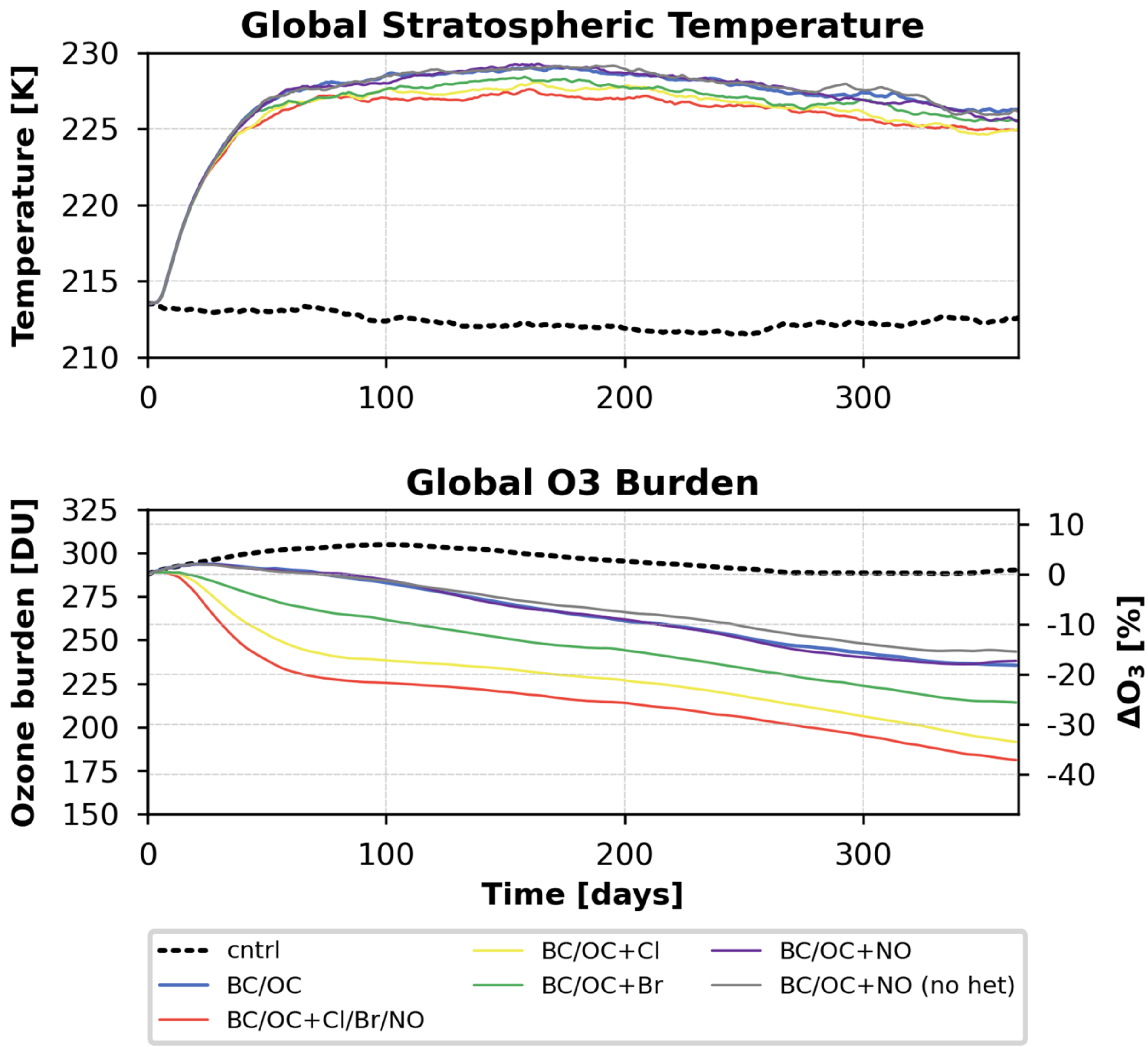
All soot is initially emitted as a constant mixing ratio **between 150 and 300 hPa** over the potential conflict regions (India-Pakistan)





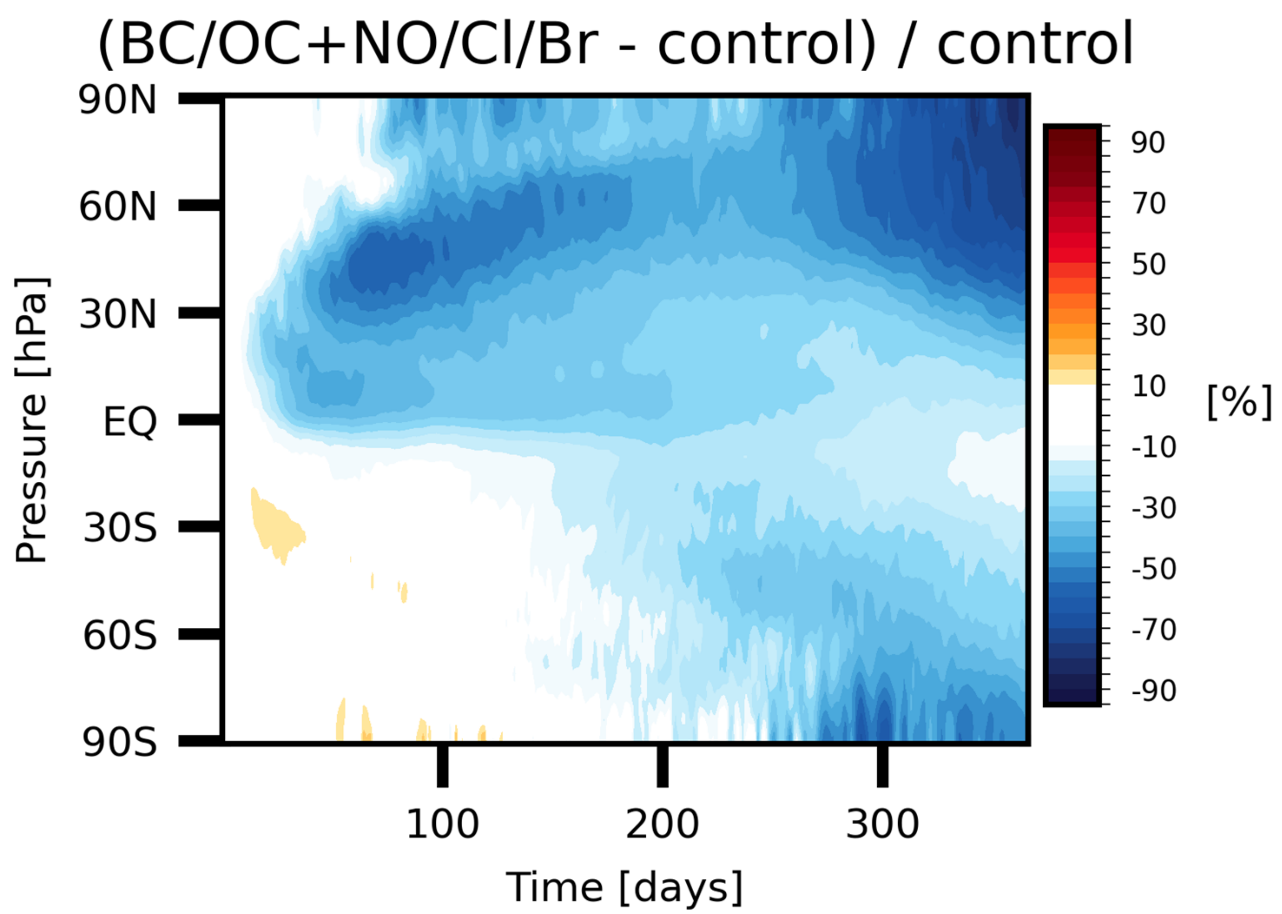
The soot plume rapidly **"self-loft"** into the stratosphere due to the BC's radiative effects

Global Temperature and Ozone Changes

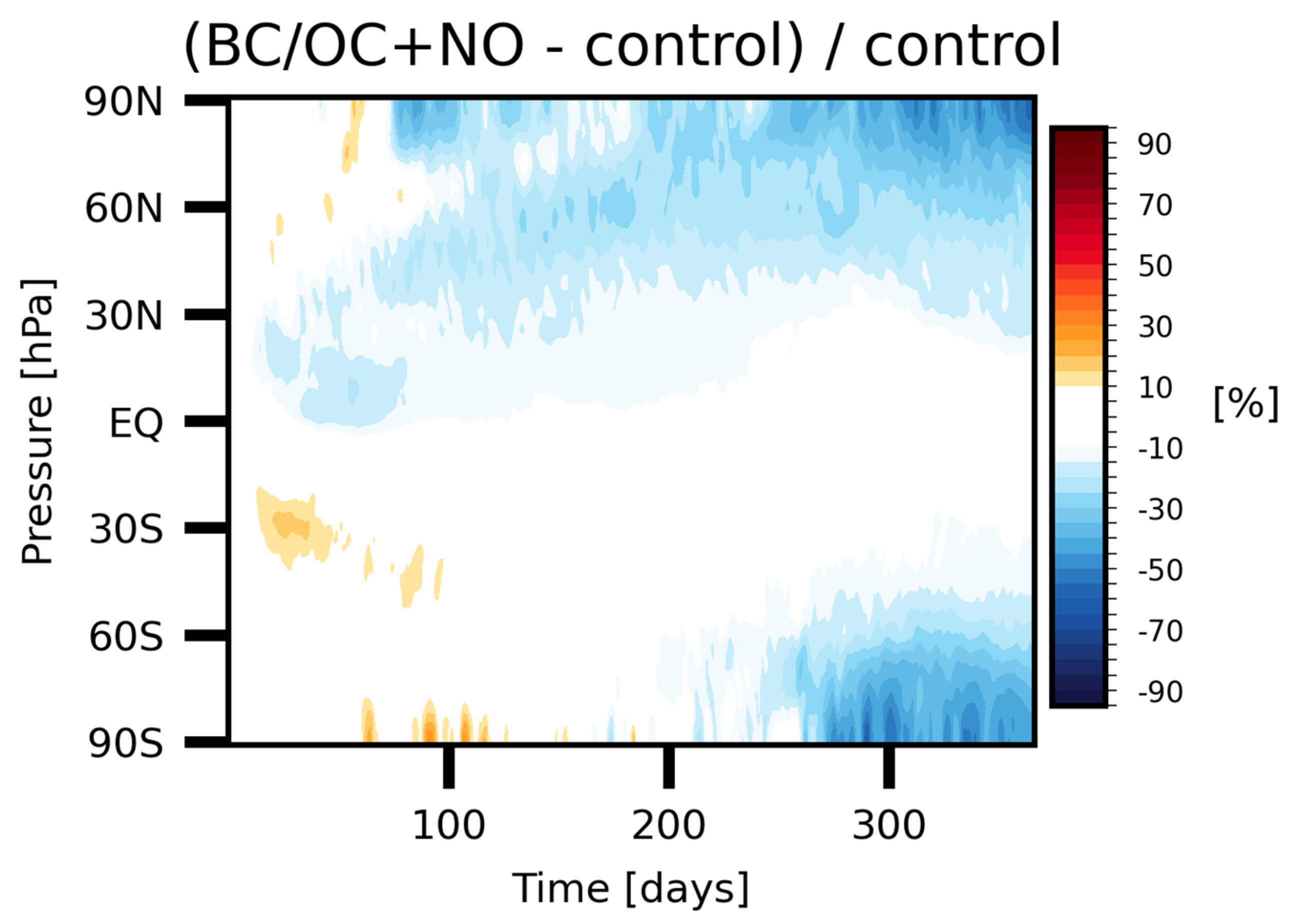


Global Column Ozone Change

New run with halogen emissions



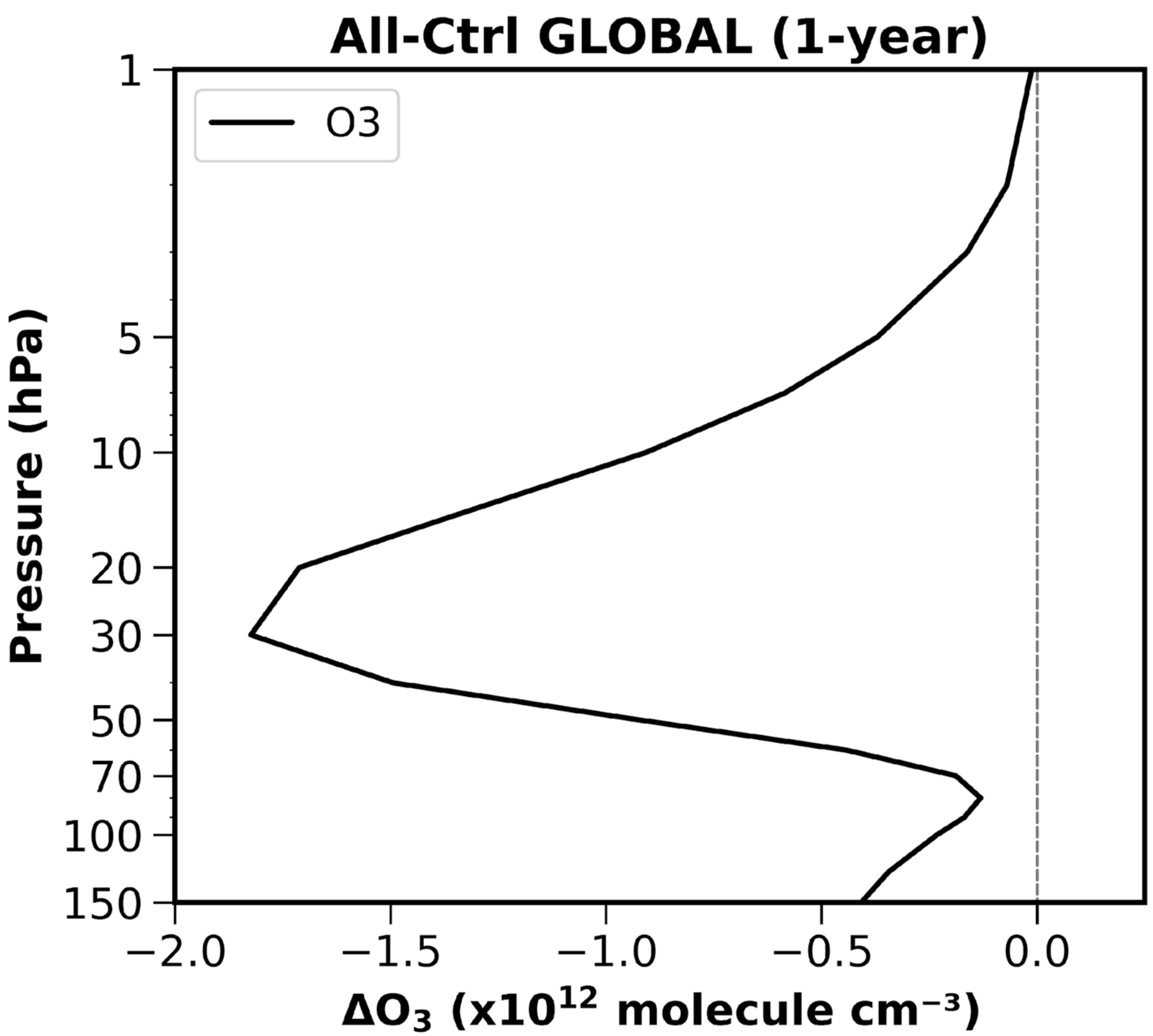
Similar to Bardeen et al. (2021)

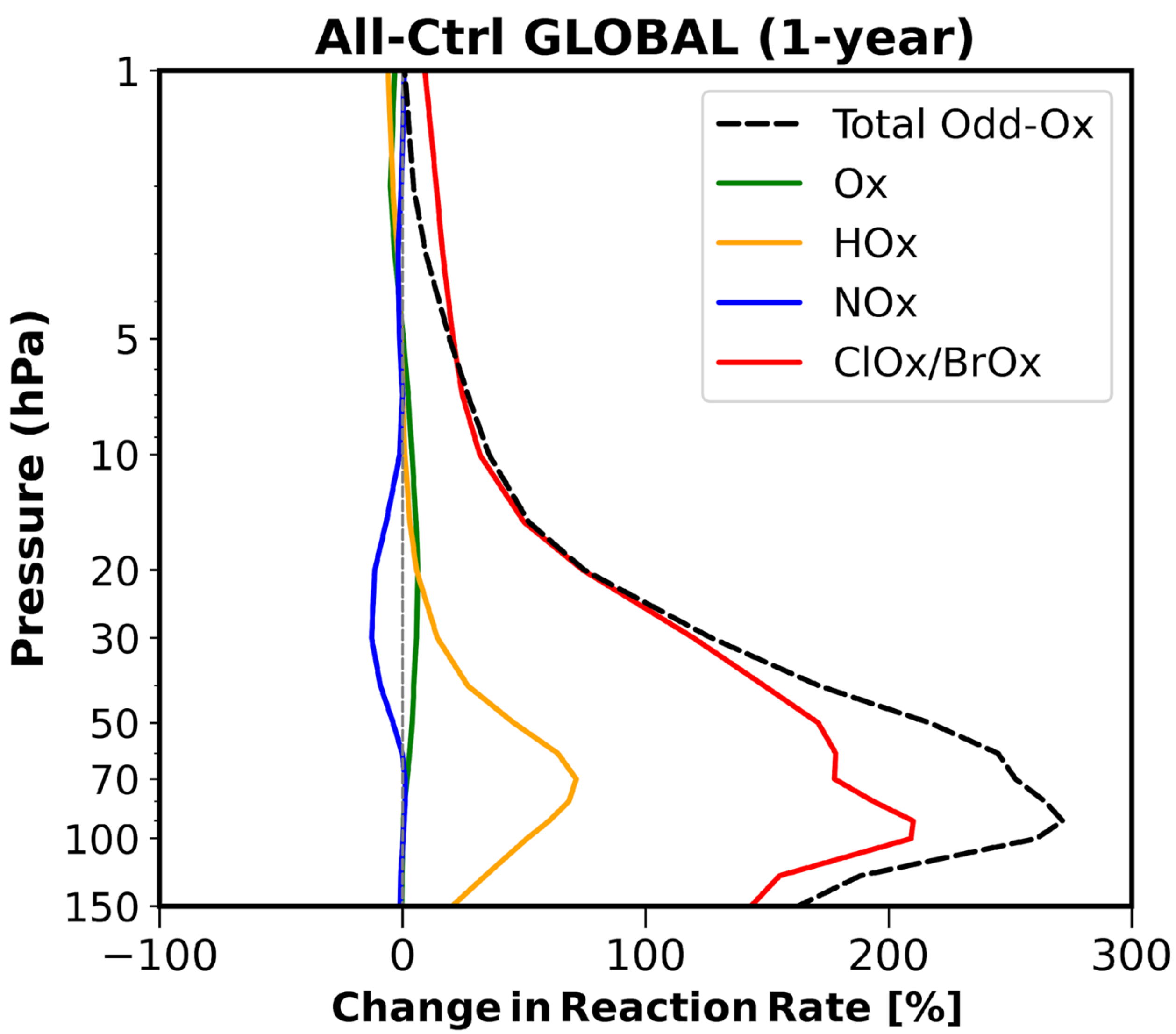


Much larger **ozone losses** over the **midlatitudes** and **polar regions** with halogen emissions

Global Ozone Change and Odd-Oxygen Loss Rates

All-emissions (BC/OC+Br/Cl/NO) minus Control

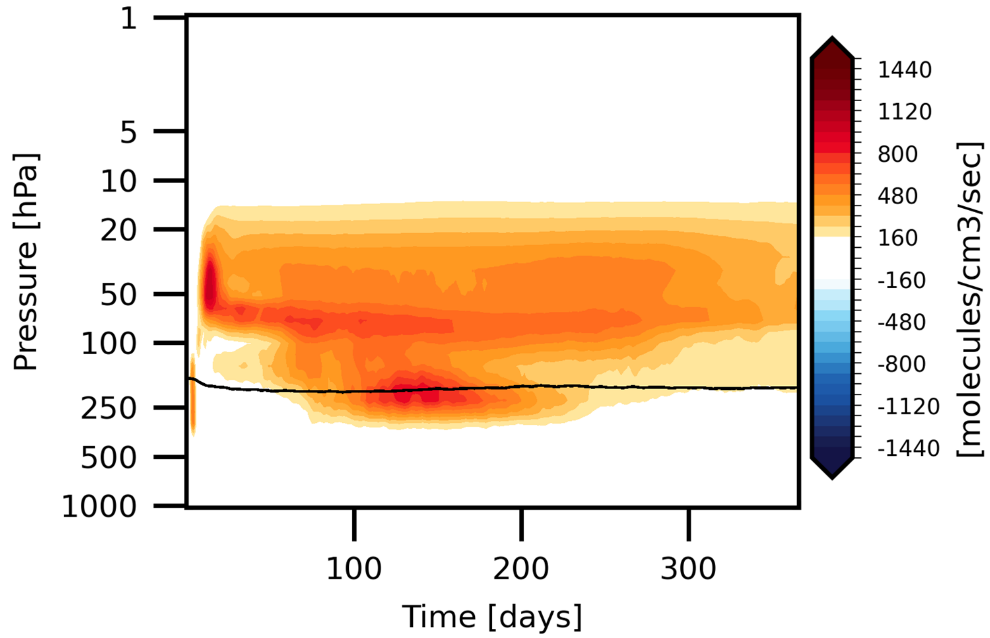




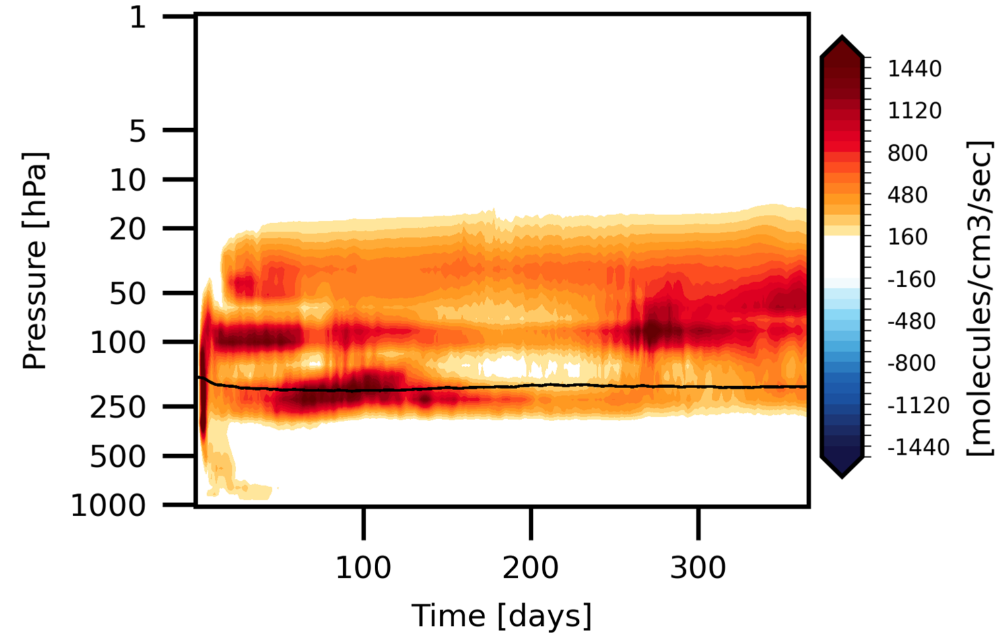
Heterogeneous Reaction Rates

(All emissions) minus (Control)

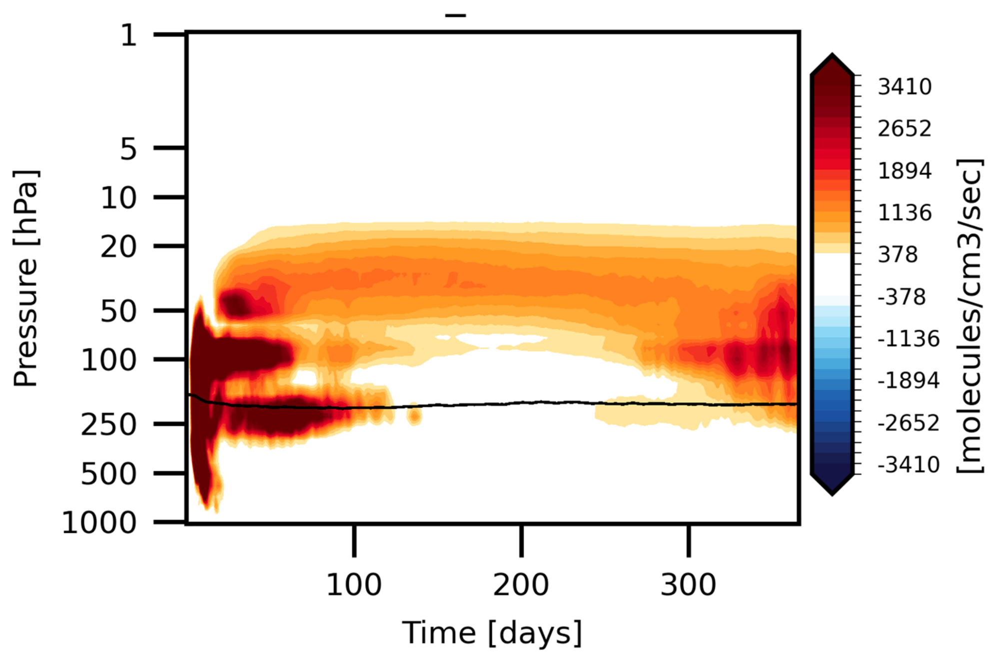
$[BrONO_2] + [HCl](liq) -> [HOBr] + [HNO_3]$



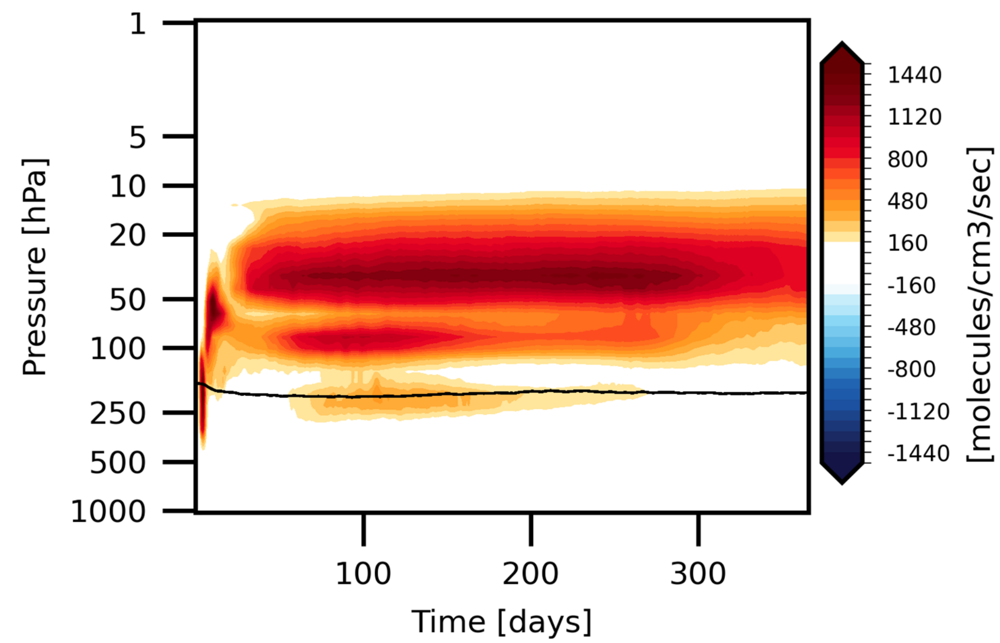
$[ClONO_2] + [HCl](liq) -> [Cl_2] + [HNO_3]$



$[HOCl] + [HCl](liq) -> [Cl_2] + [H_2O]$

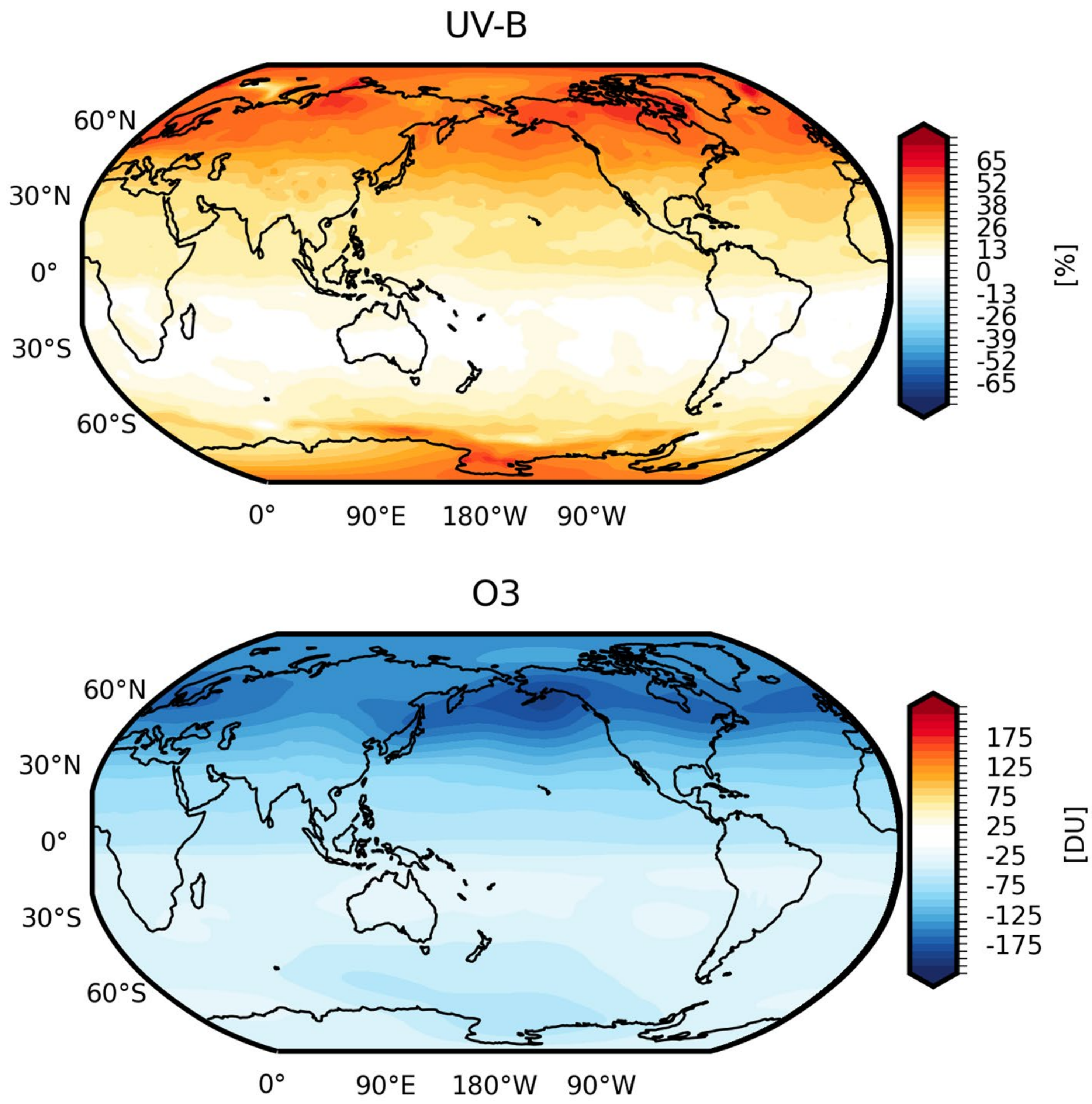


$[HOBr] + [HCl](liq) -> [BrCl] + [H_2O]$



Enhanced heterogeneous reactions for Cl activation!

Surface Impact



Conclusion

Our results show that a regional war scenario releasing 5 Tg of soot could cause approximately a 40% reduction in global ozone within the first year of the simulation.

This loss is driven by two main mechanisms: (1) stratospheric warming, which accelerates chemical reaction rates, and (2) enhanced catalytic cycles from halogen emissions on smoke particles.

The resulting ozone depletion leads to substantially increased global UV-B exposure, indicating that even a regional nuclear war could trigger serious global environmental consequences.

Q & A

Particle and Gas Emissions from Urban Fires (India-Pakistan case)

India/Pakistan Scenario
(Bardeen et al. 2021)

Black Carbon
5 Tg

BC/fuel ~ 20g/kg

Organic Carbon
1.66 Tg

BC:OC = 70:30

NOx
0.5 Tg + Fireball

Fire: 2g/kg
Fireball: 10^32 molecules of NO injected per Mt of yield

Fuel 250 Tg
(11,000 kg per capita)

Toon et al. 2007

* figure generated by generative AI

Chlorine
3.25 Tg

Cl ~ 0.8 Tg
3.2 g/kg (waste combustion, US EPA)
3.56 g/kg (structure, Holder)
2.5 g/kg (Vehicle, Holder)
4.12 g/kg (vehicle, SZEWCZYŃSKI, 2023)
0.06 g/kg (flaming combustion, Butler & 2006)
0.06 g/kg (biomass combustion, Andreae 2019)

HCL ~2.65 Tg
11 g/kg (structure, Holder)
6.4 g/kg (Vehicle, Holder)
0.35 g/kg (biomass, Holder)

Bromine
0.08 Tg

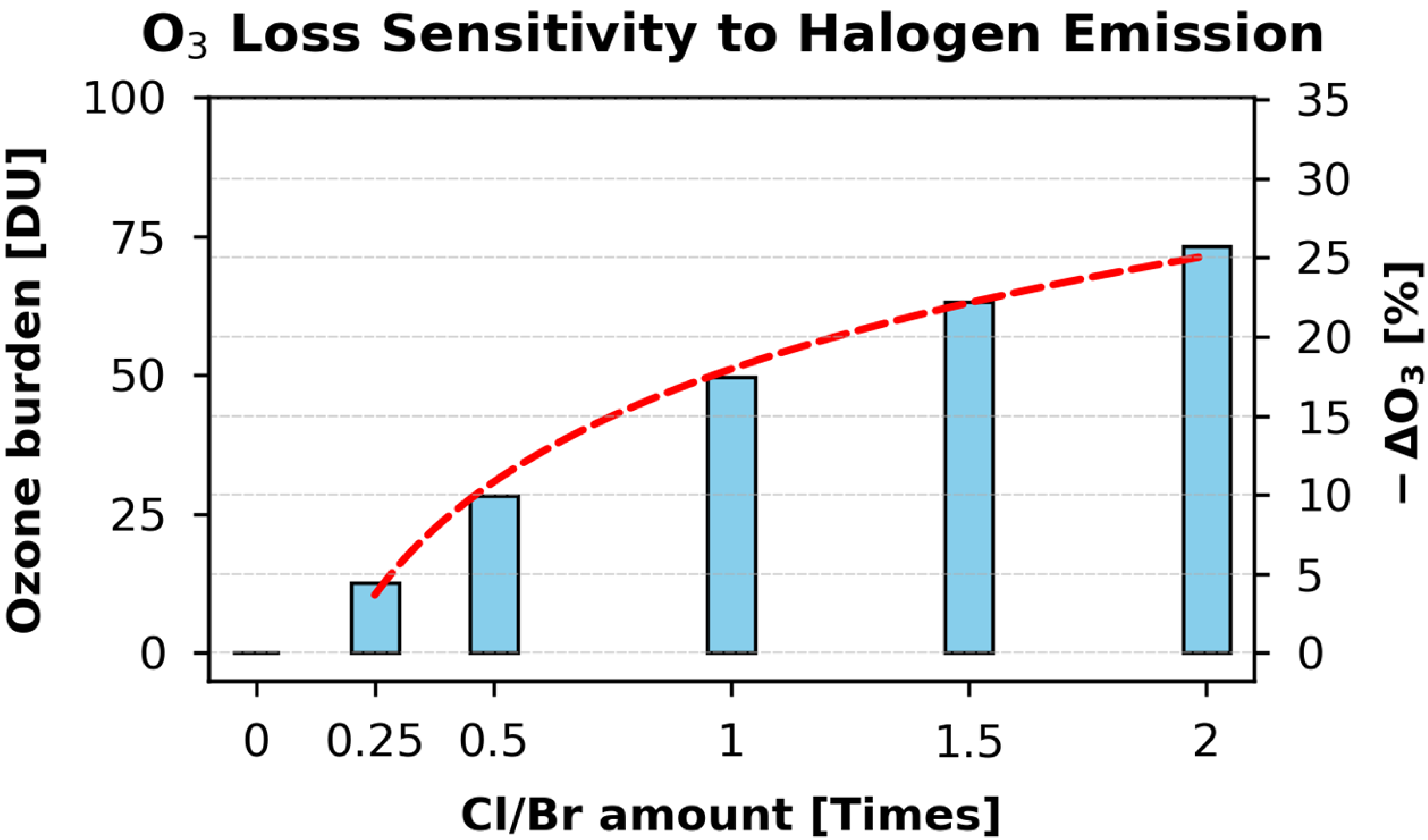
Br ~ 0.003 Tg
0.005 g/kg (structure, Holder)
0.26 g/kg (vehicle, holder)

HBr ~ 0.074 Tg
0.005 g/kg (structure, Holder)
0.26 g/kg (vehicle, holder)

Are These Ozone Anomalies Linearly Proportional to the Halogen Forcing?

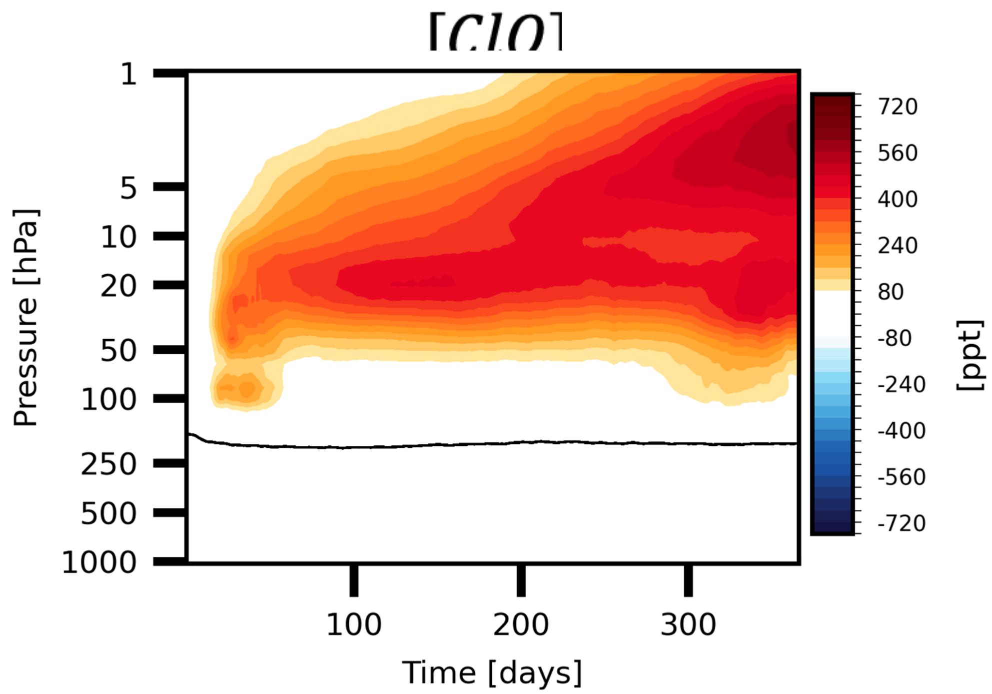
$$\Delta O_3 = O_3(BC/OC + NO + Cl/Br\times\alpha) - O_3(BC/OC + N($$

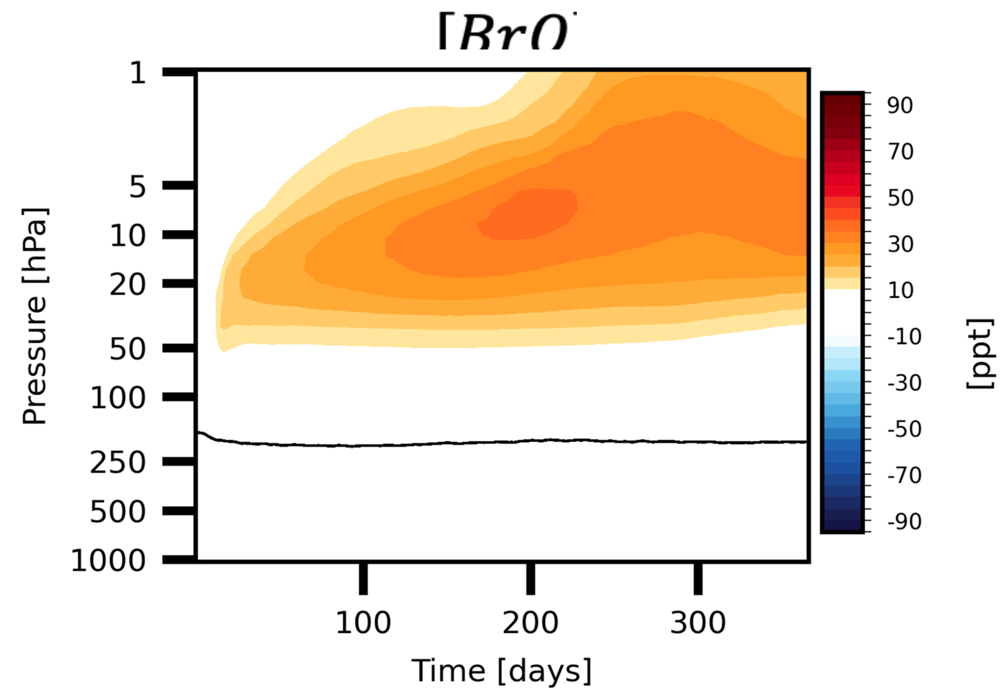
$$\Delta O_{3\,\%} = \Delta O_3/O_3(Control) * 1($$



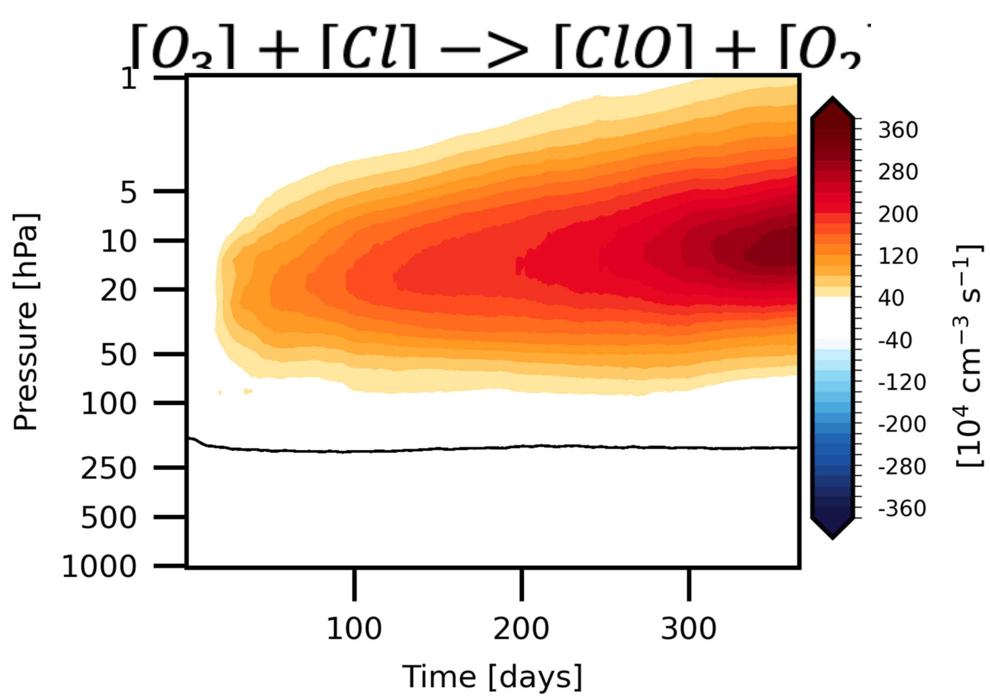
Changes in Halogen Burden / Loss Rates

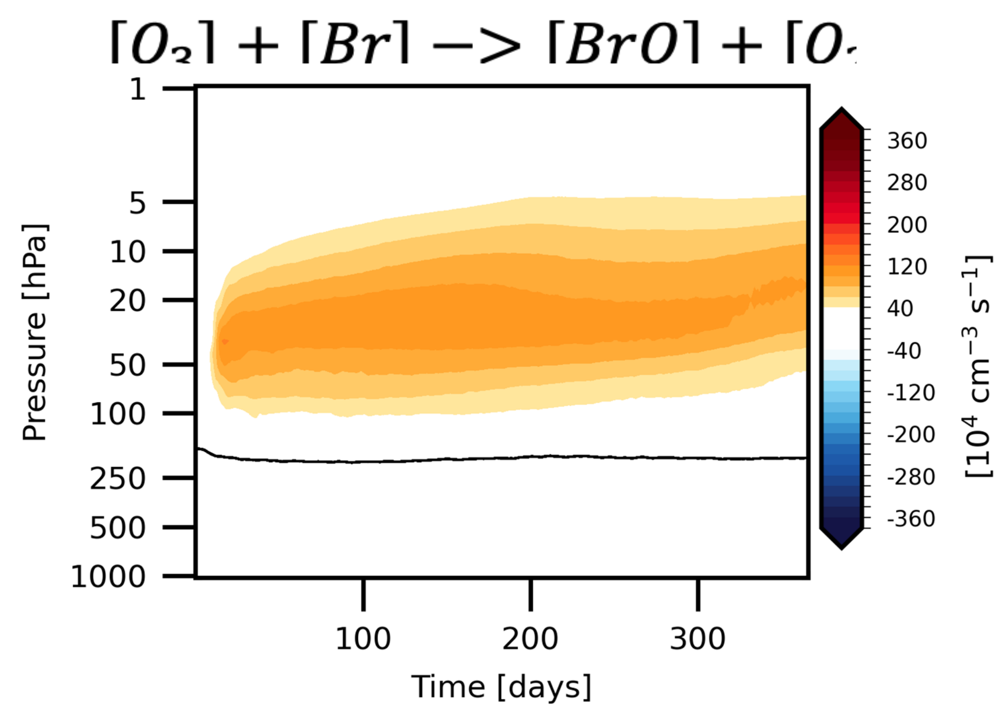
(All emissions) minus (Control)





Ozone Loss Rates from

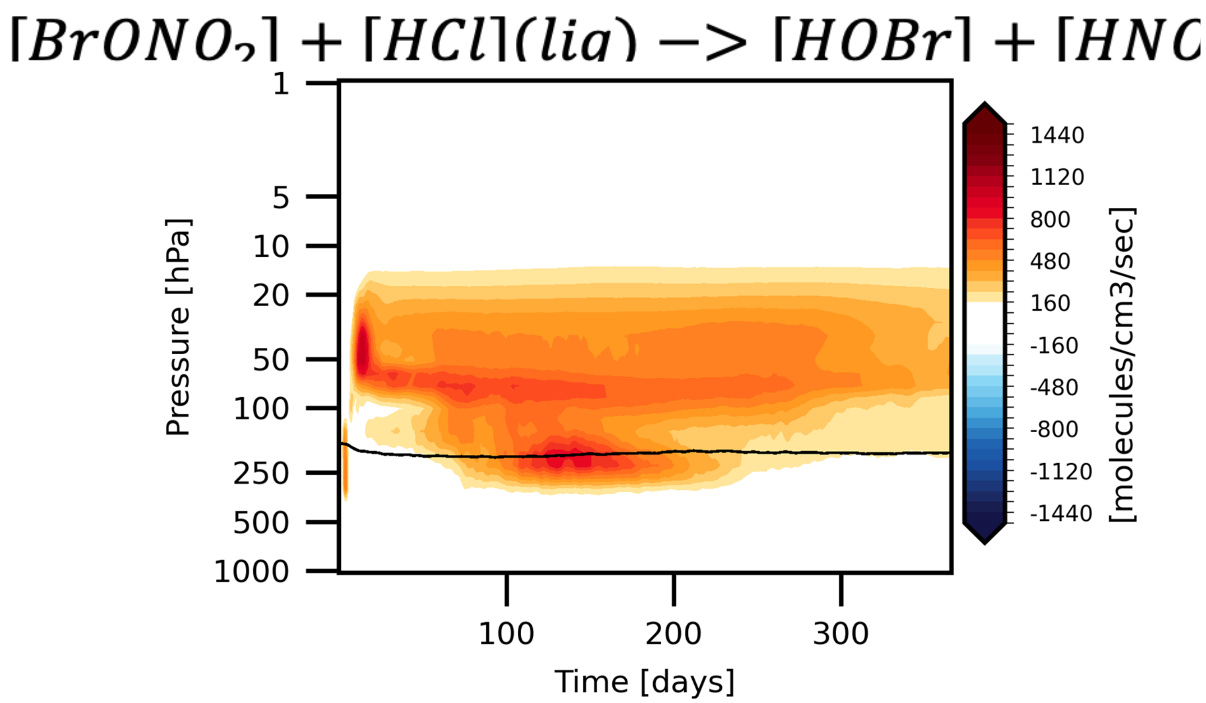


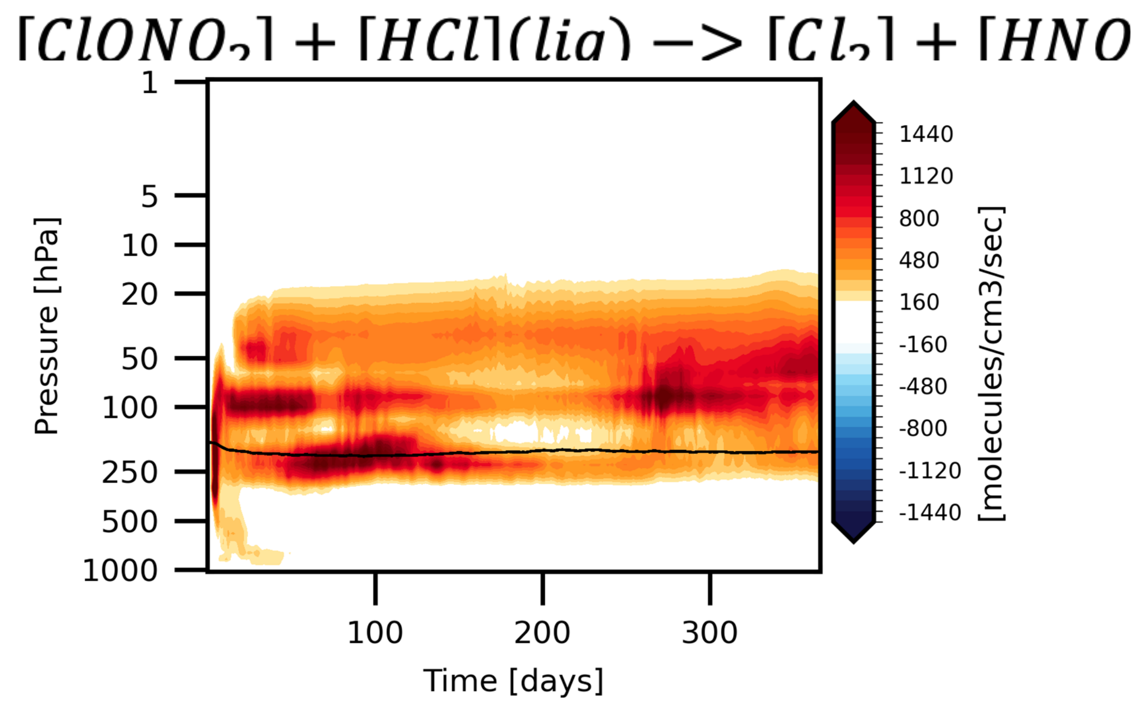


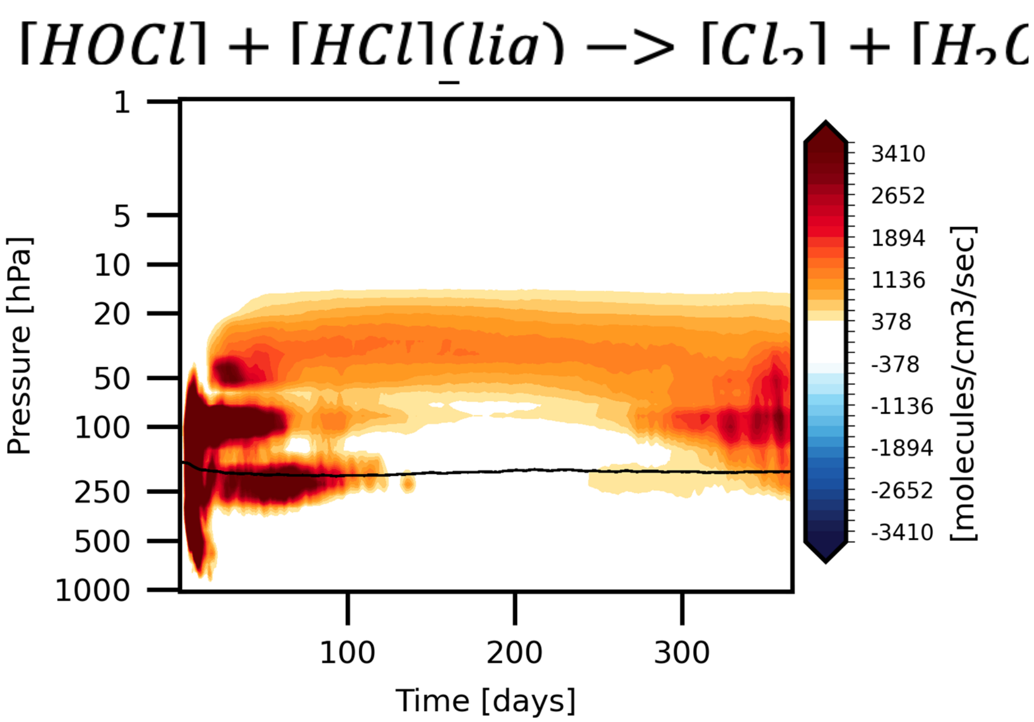
Substantial increase in reactive Cl/Br species as well as the reaction rates!

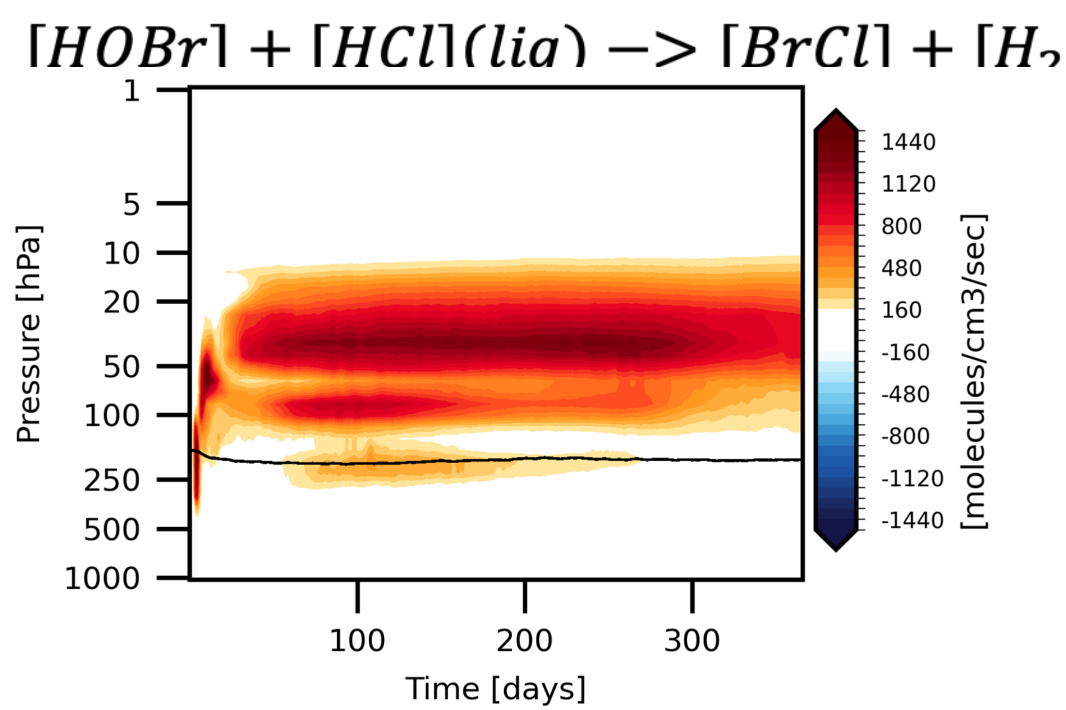
Heterogeneous Reaction Rates

(All emissions) minus (Control)





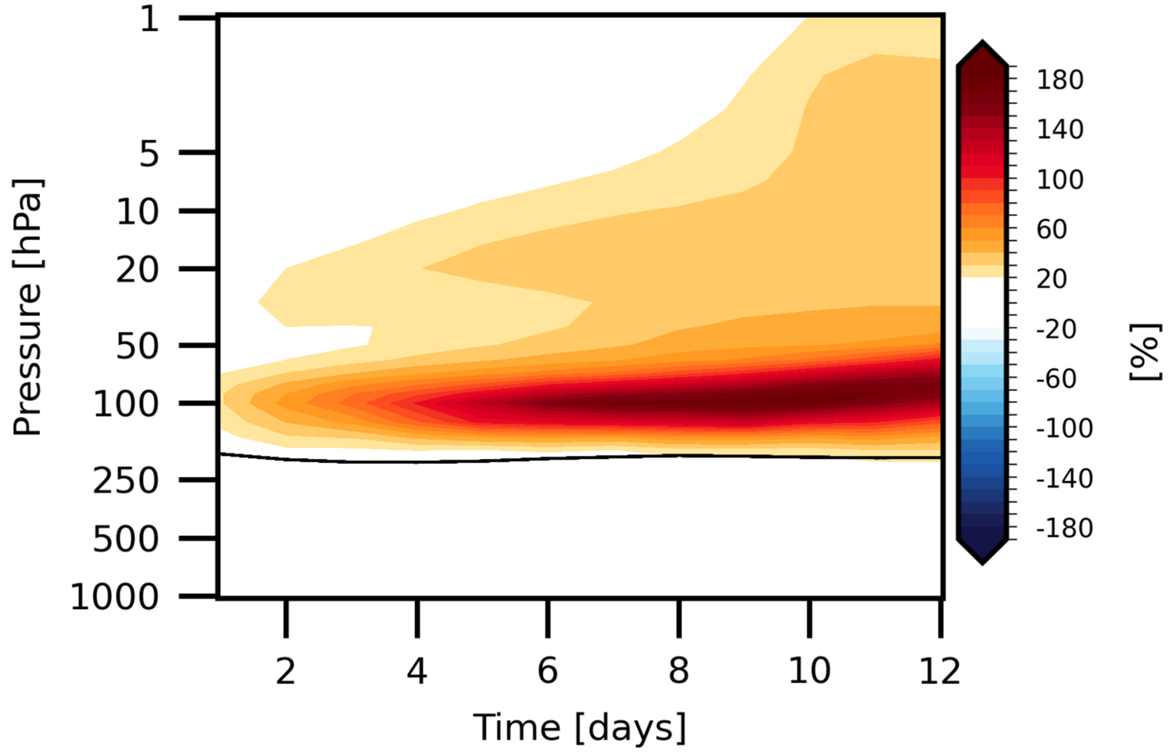




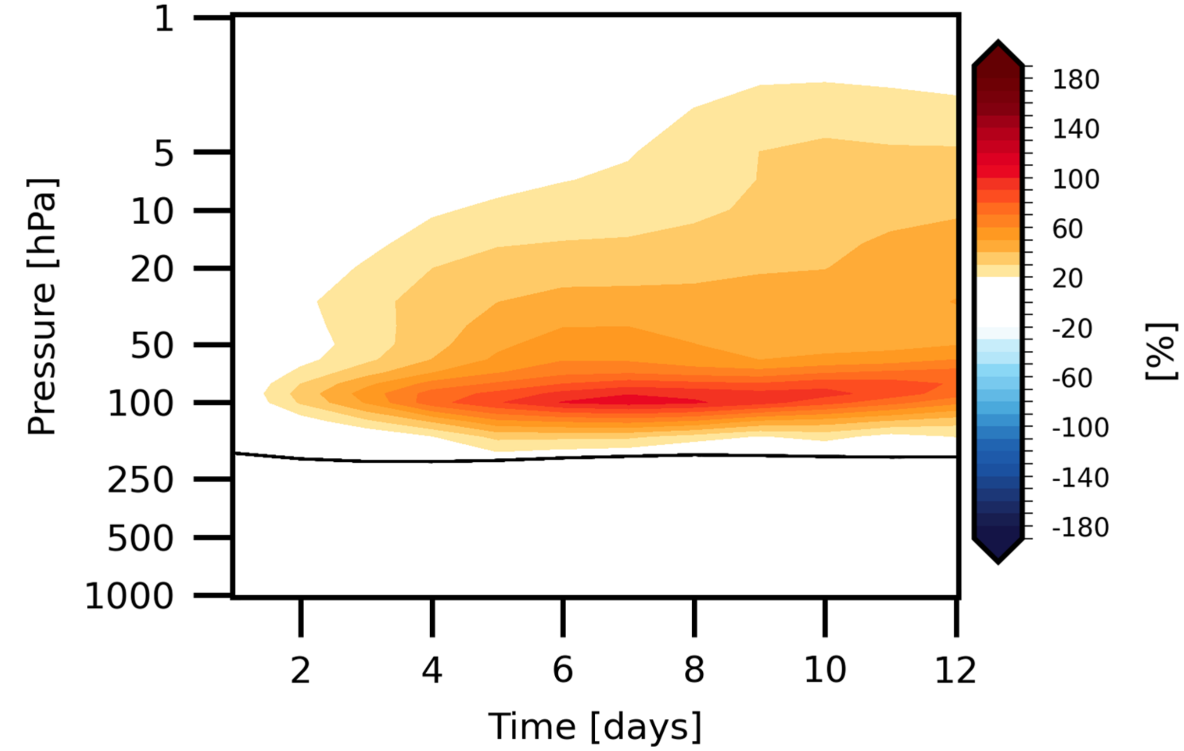
Also in heterogeneous reactions for halogen activation

Water Vapor and HOx Cycle (BC/OC minus Control)

$\Delta[H_2O]$

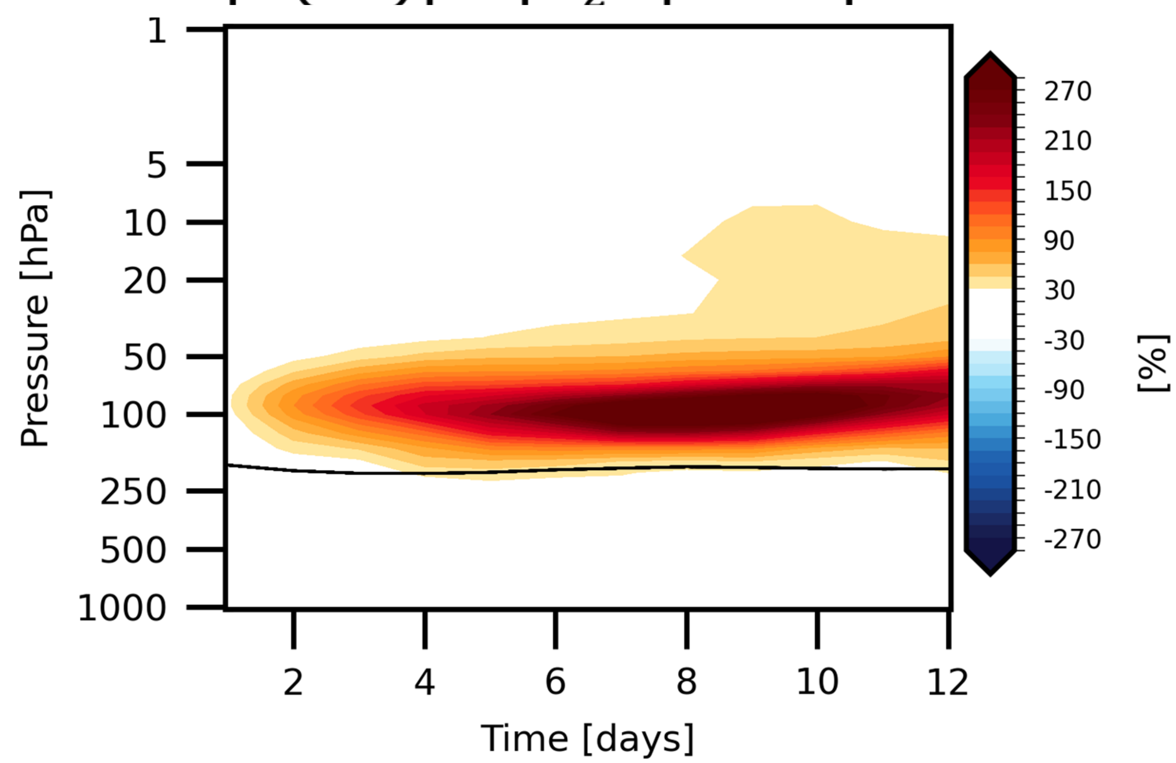


$\Delta[OH]$

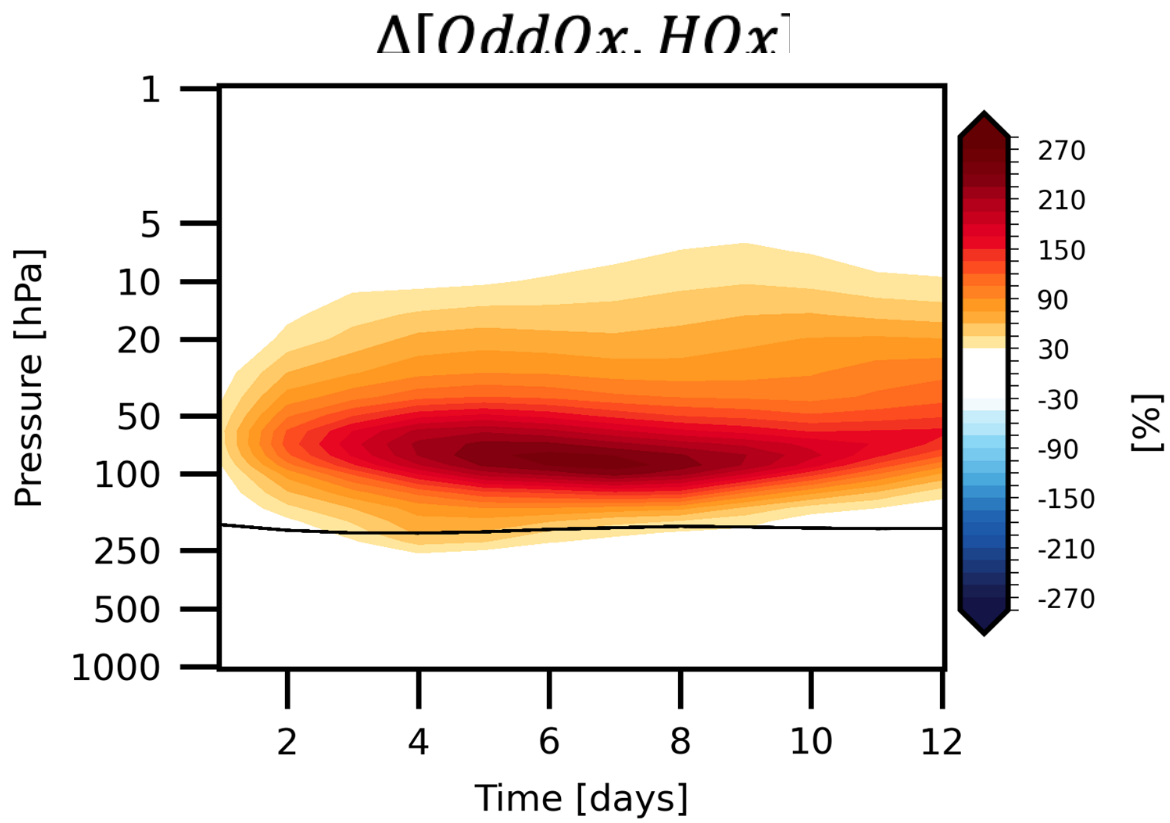


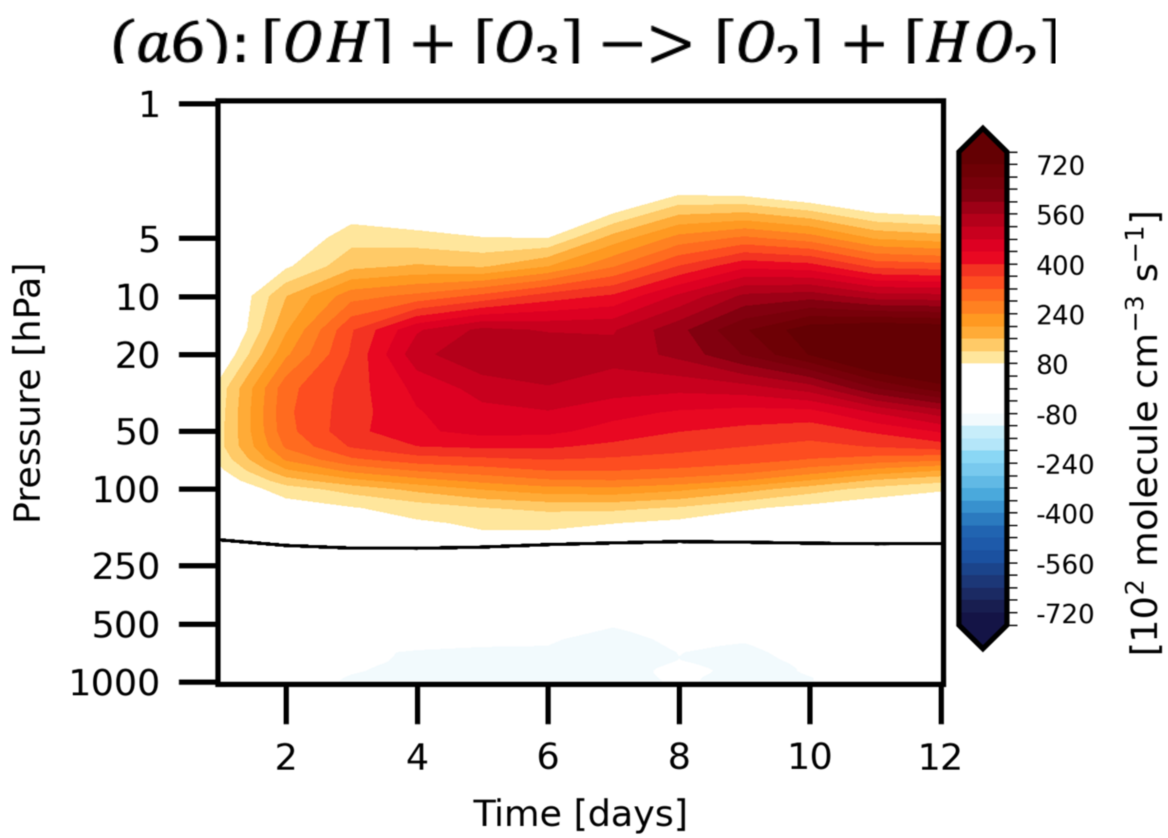
OH production

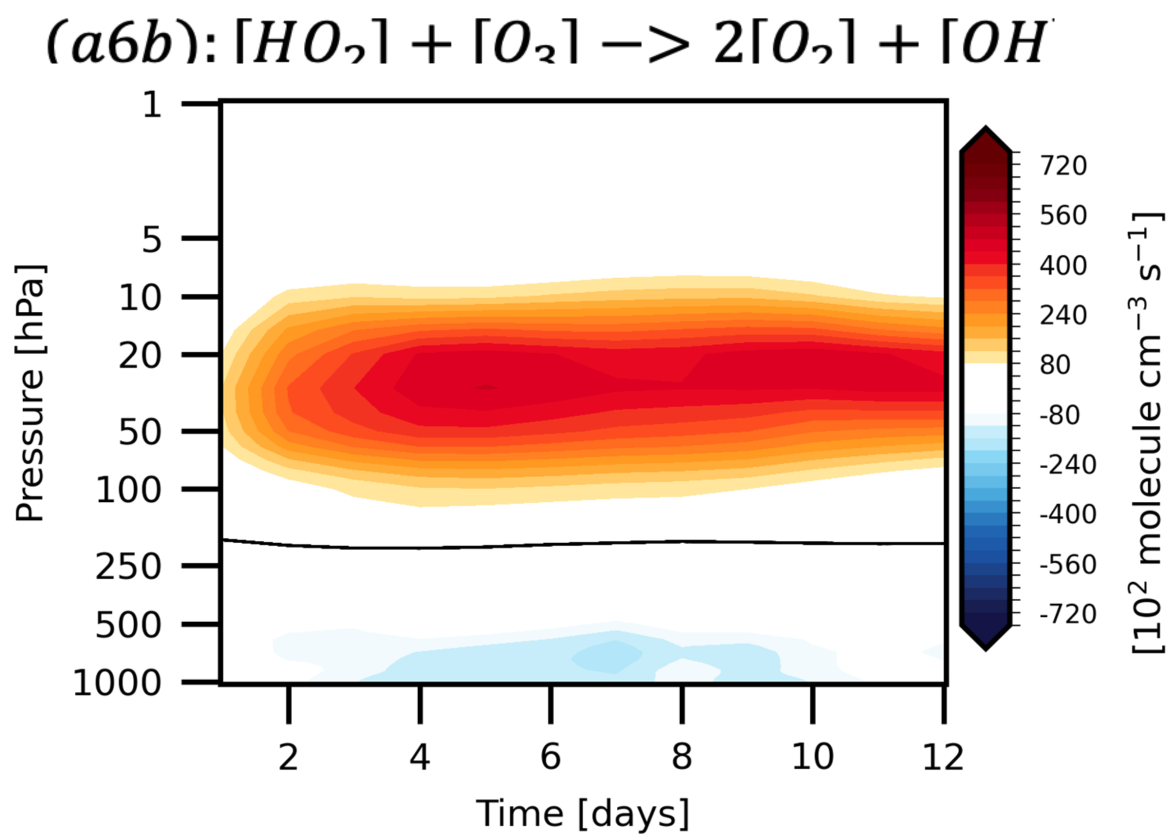
$[O(^1D)] + [H_2O] -> 2[OH$



Water Vapor and HOx Cycle (BC/OC minus Control)



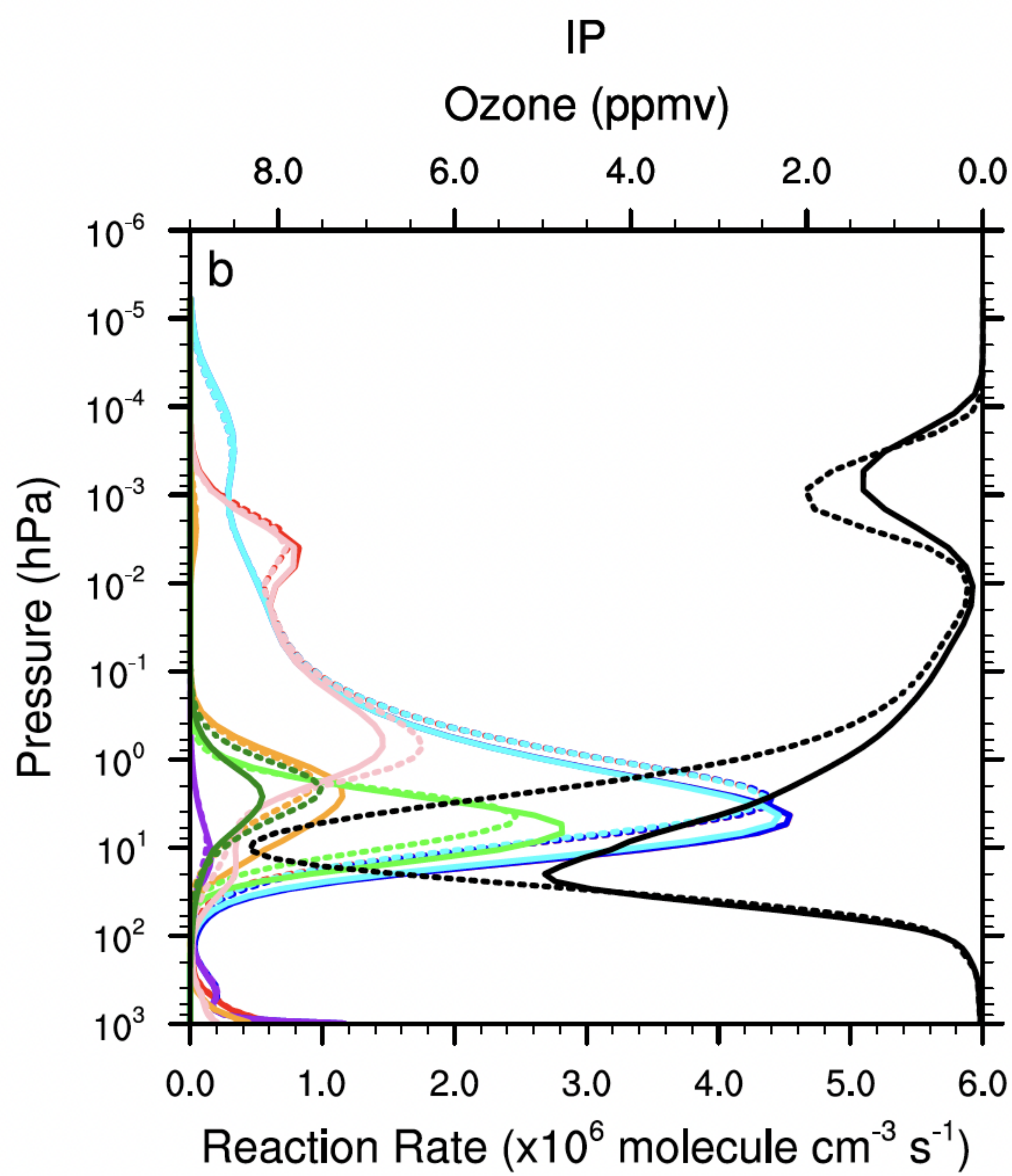




Inconsistency in the NOx Loss Rates?

Solid line: 5Tg-Nuclear war case
Dashed line: Control case

NOx cycle (green) is contributing to the enhanced ozone loss!

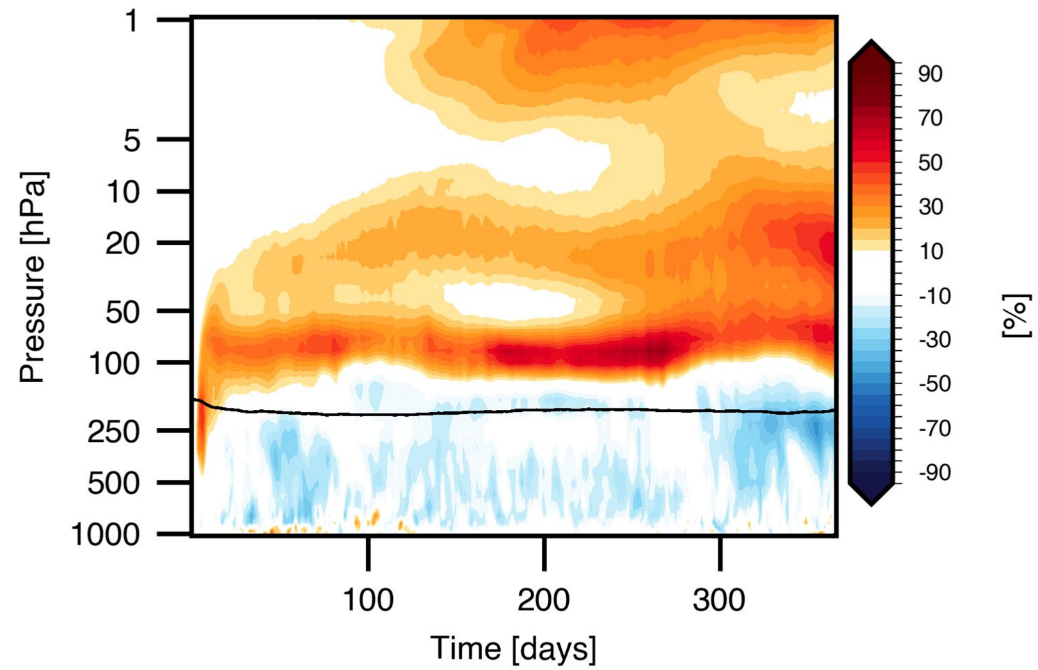


From Bardeen et al. (2021)

Ozone Loss Rate from NOx Cycle

A run similar to Bardeen et al.

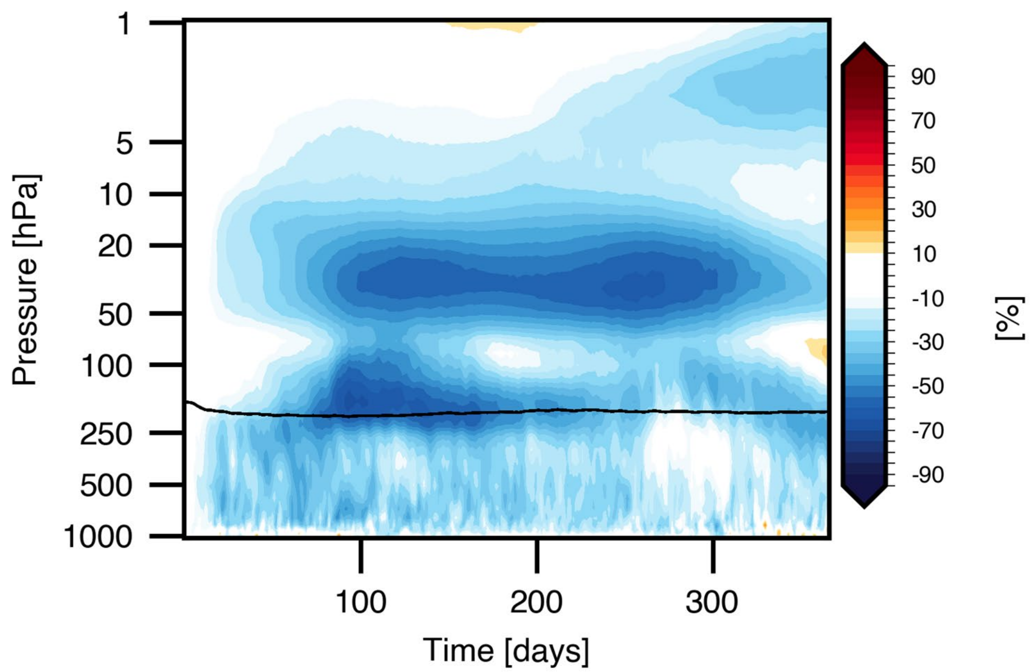
(BC/OC+NO) minus (Control)



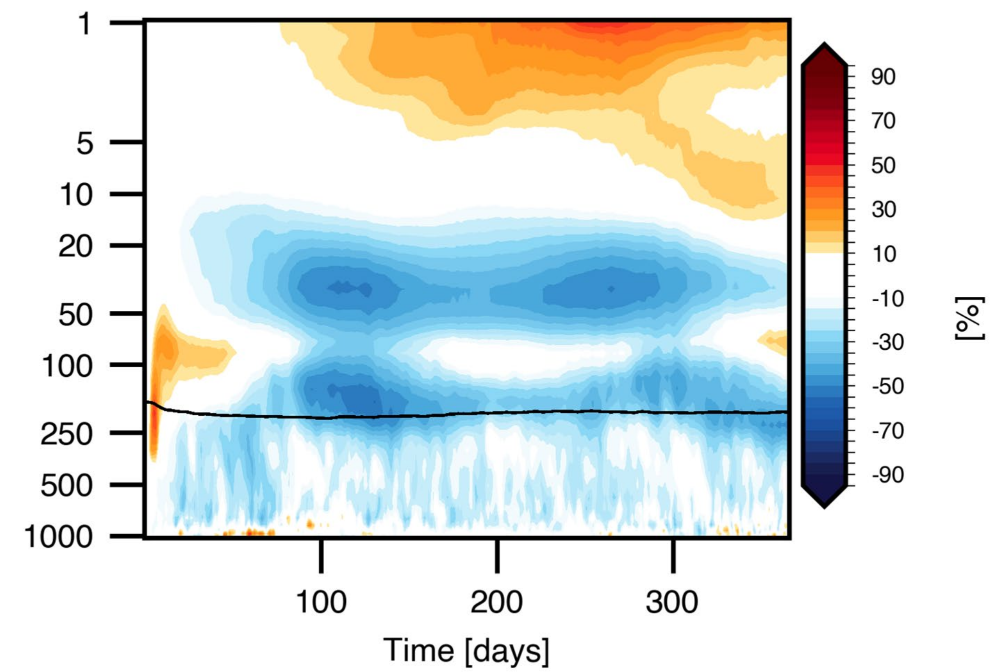
Enhanced ozone loss from NOx cycle

Runs with the updated chemistry

(BC/OC+NO/Br/Cl) - (Control)



(BC/OC+NO) - (Control)



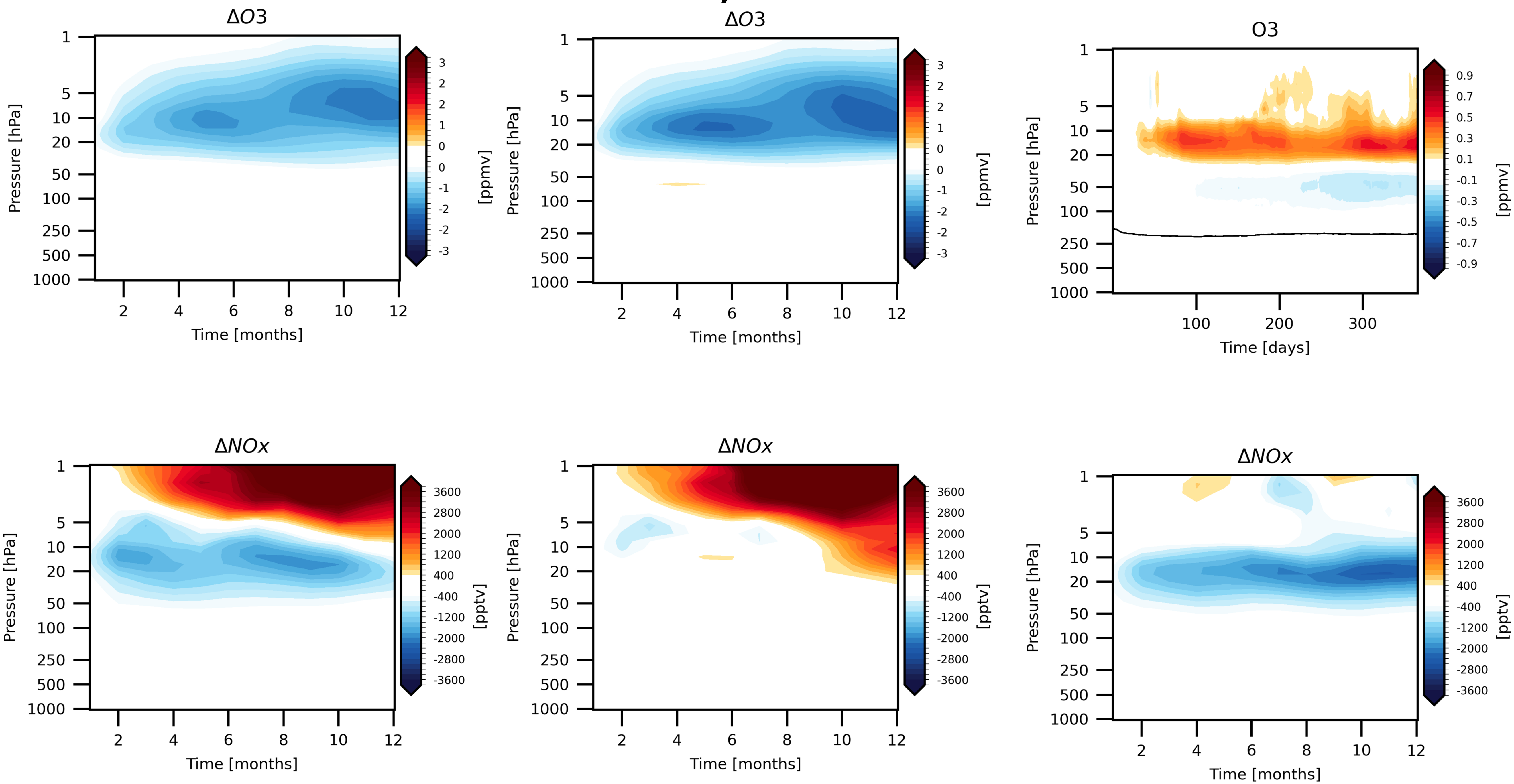
Reduced loss of ozone from NOx cycle

Role of Heterogeneous Chemistry on NOx

(a) my new run (BC/OC+NO) - ctrl

(b) ref. run (BC/OC+NO) - ctrl But without updated heterogeneous chemistry

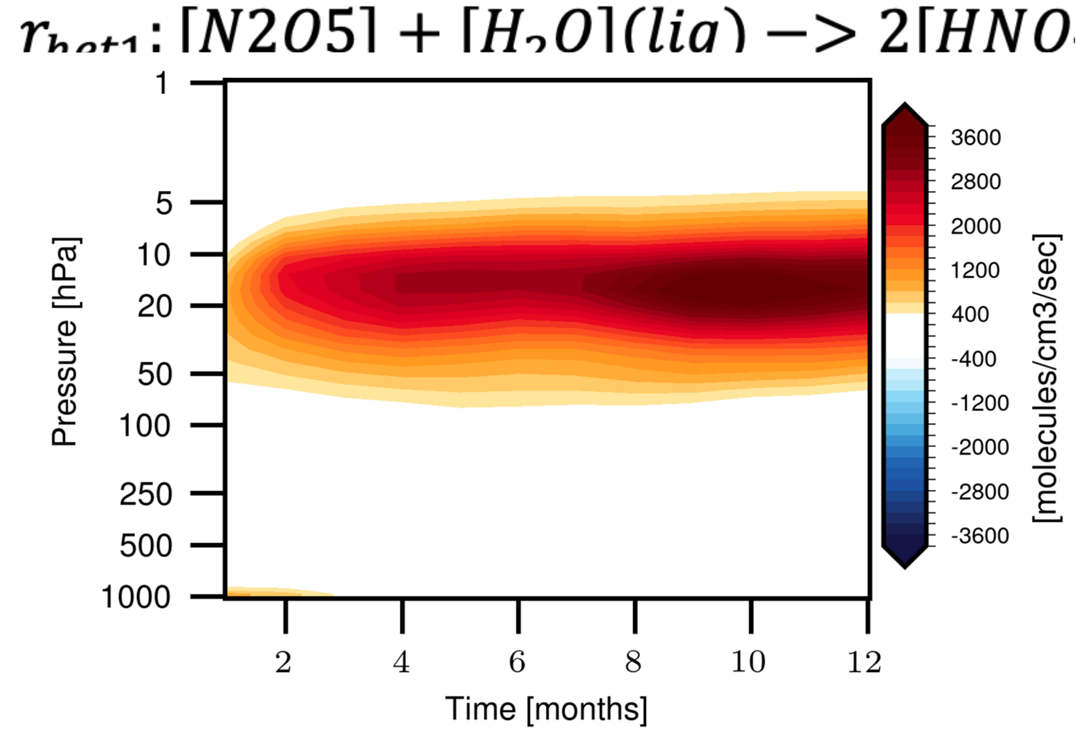
(a) minus (b) (new chemistry on - off)

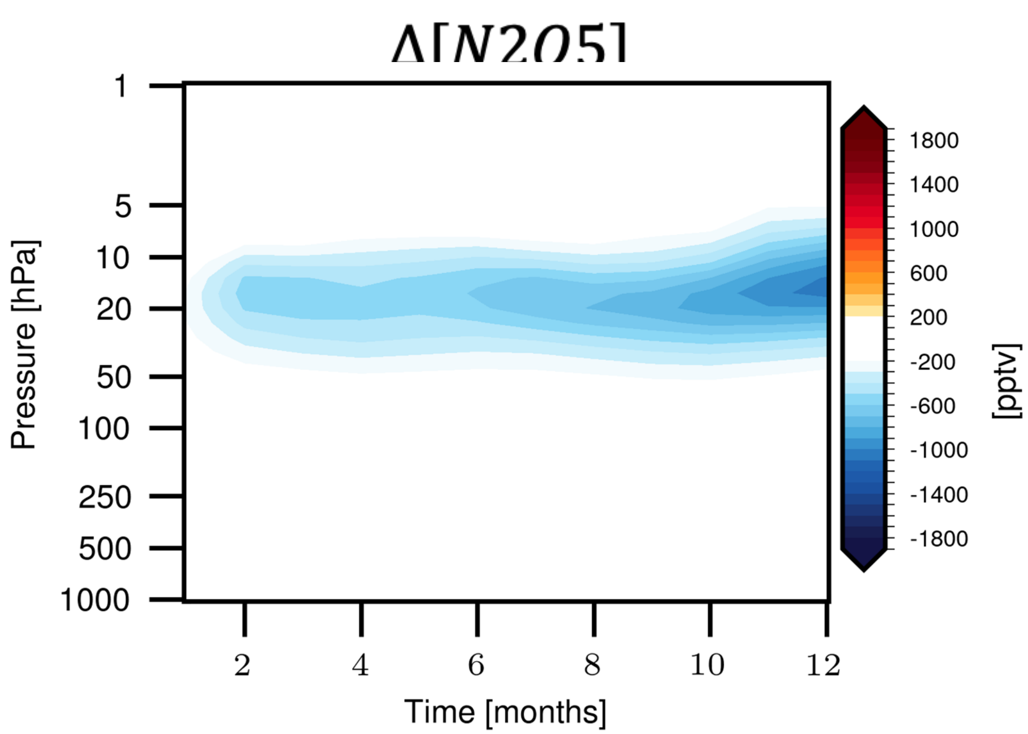


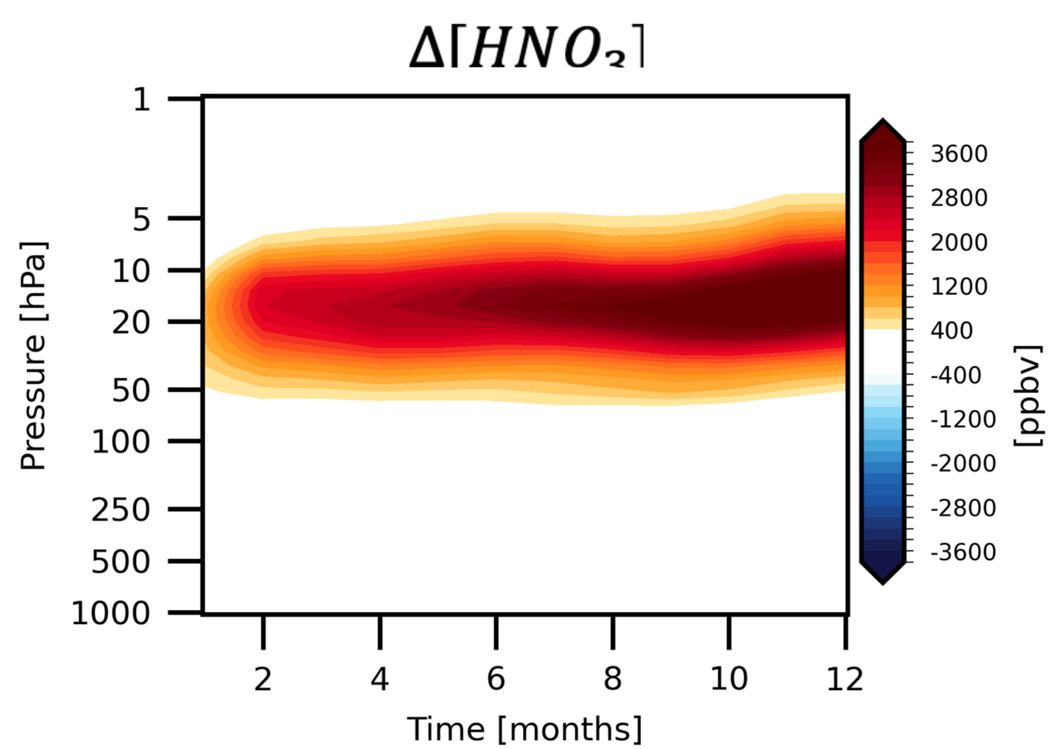
Role of Heterogeneous Chemistry on NOx

(new chemistry on - off)

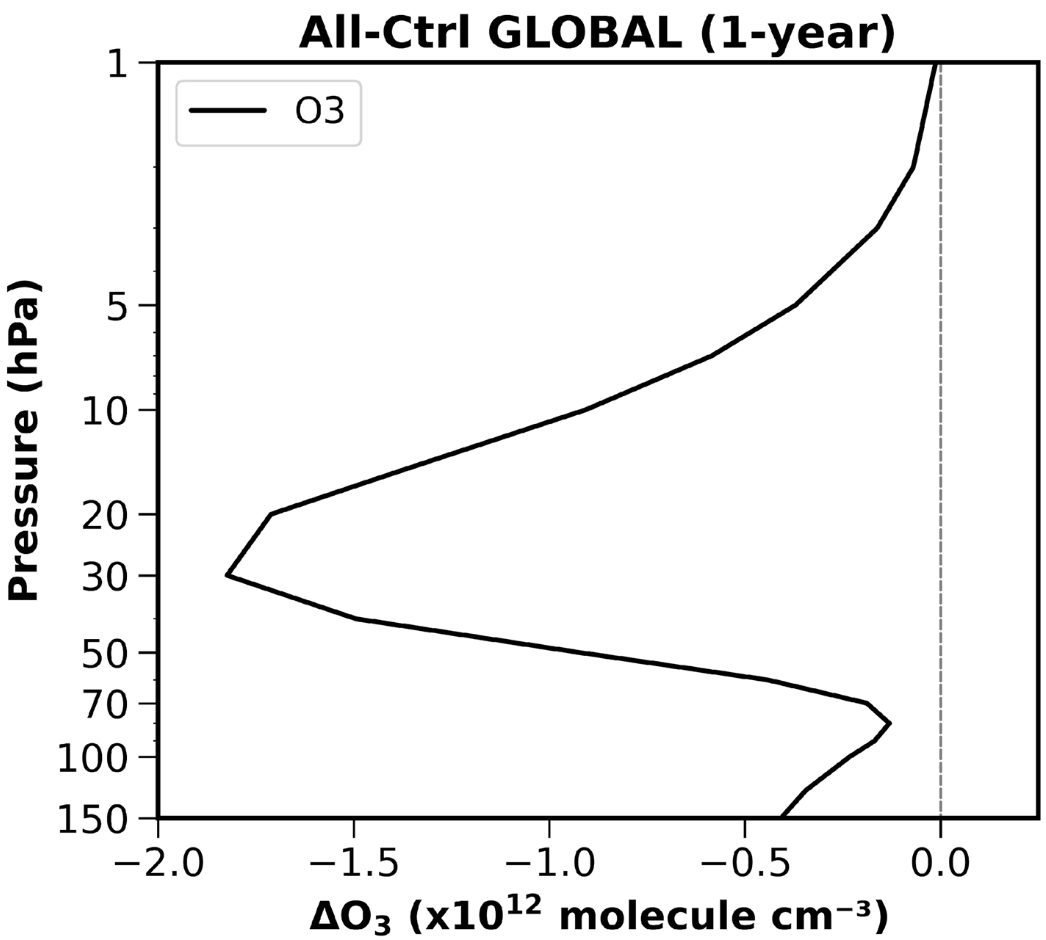
NAT aerosol reaction

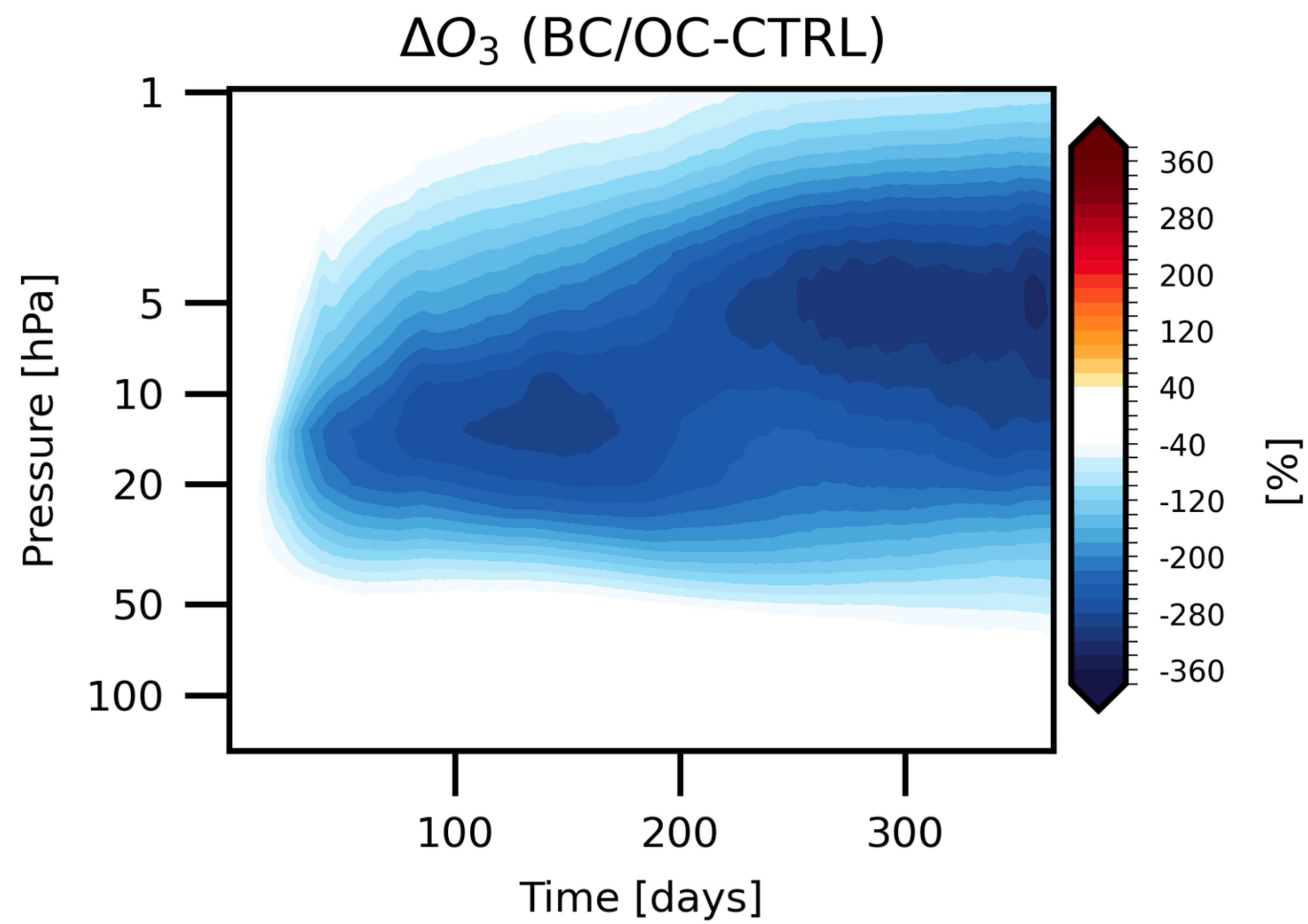






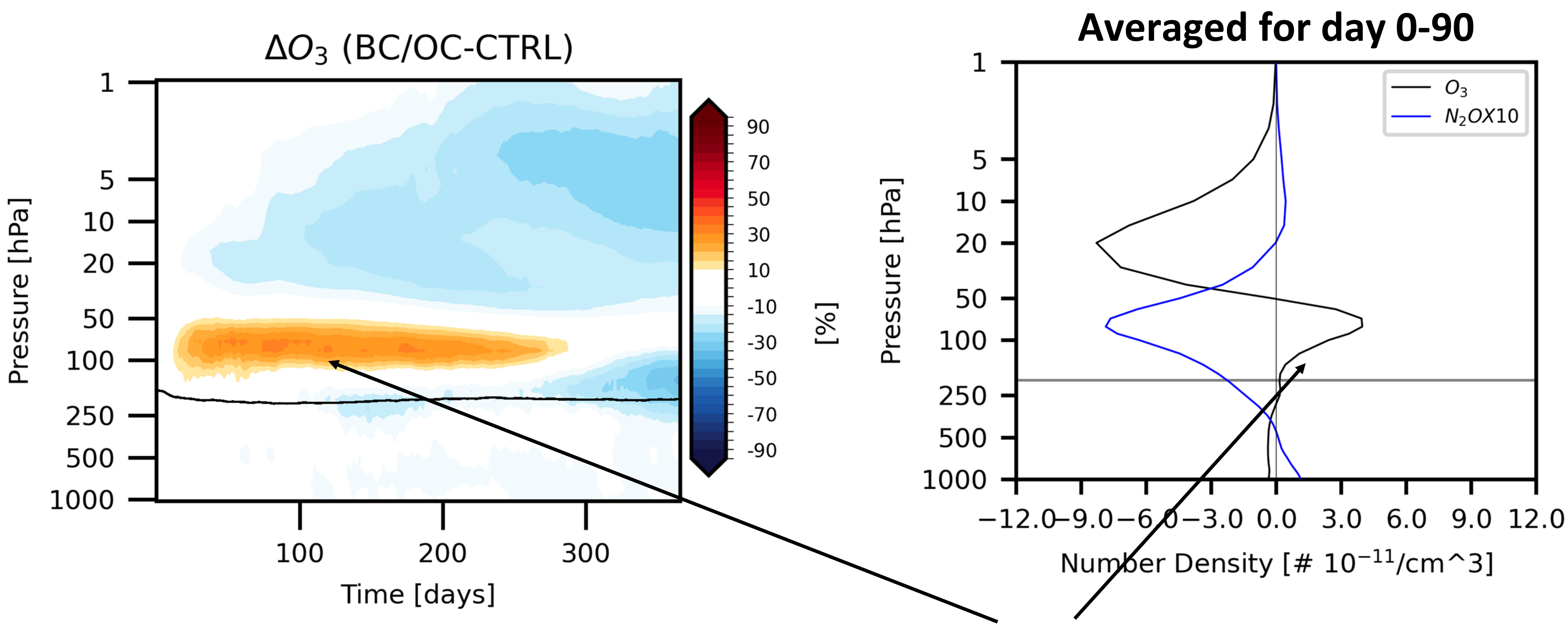
All-emissions minus Control





Changes in Ozone Transport

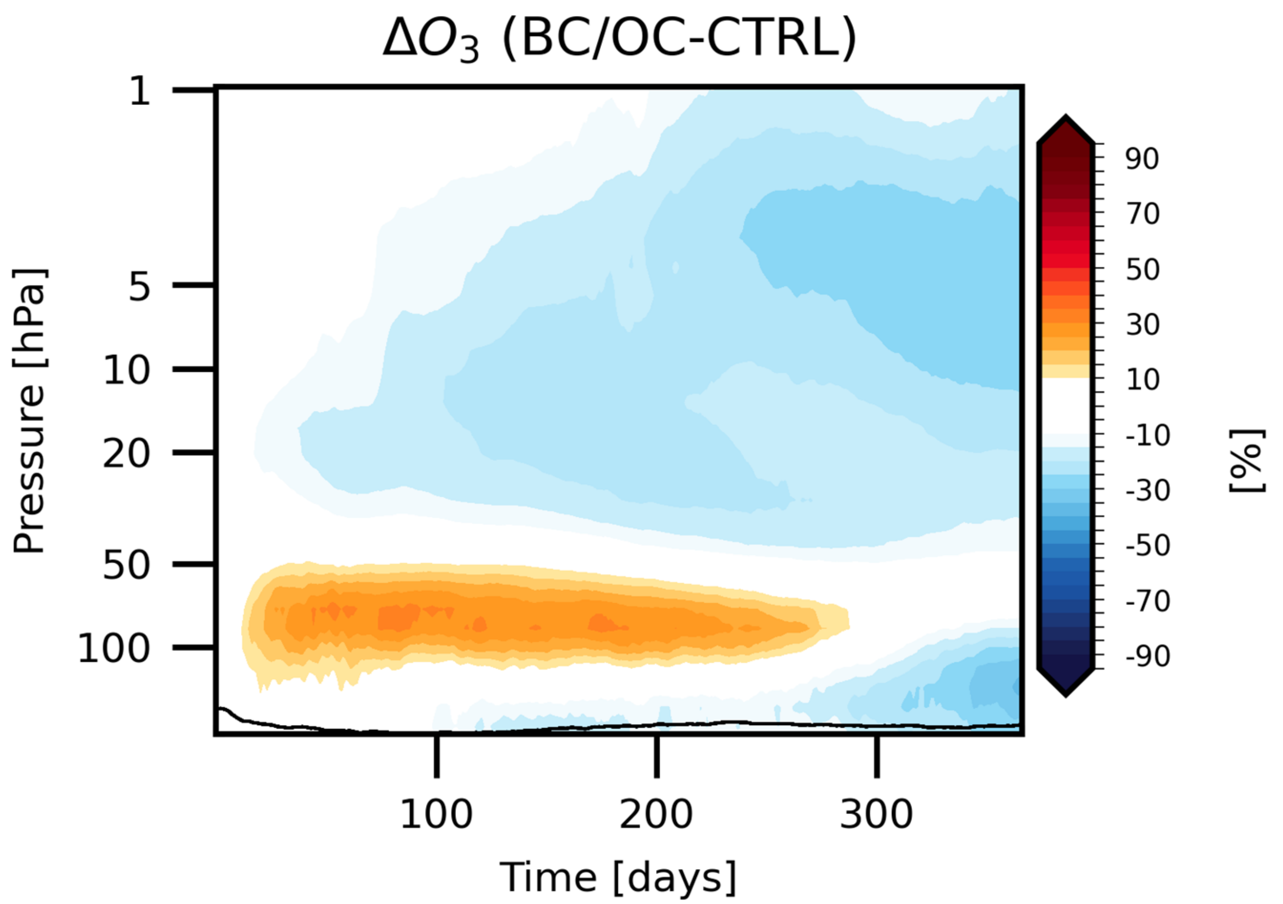
(BC/OC only) minus (Control)



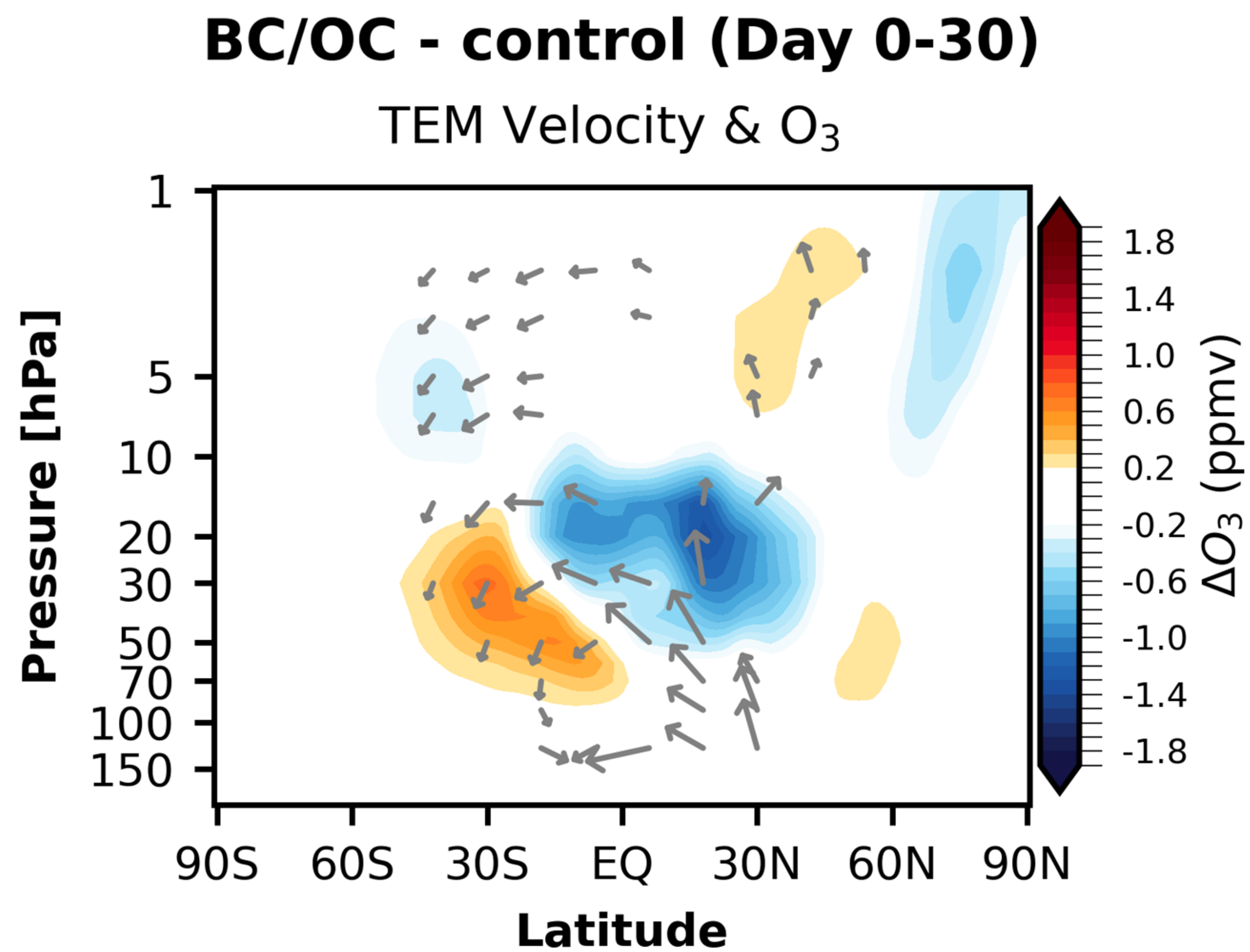
At ~70 hPa, positive anomalies in ozone

The negative N_2O anomaly indicates that these are associated with transport

Changes in Ozone Transport



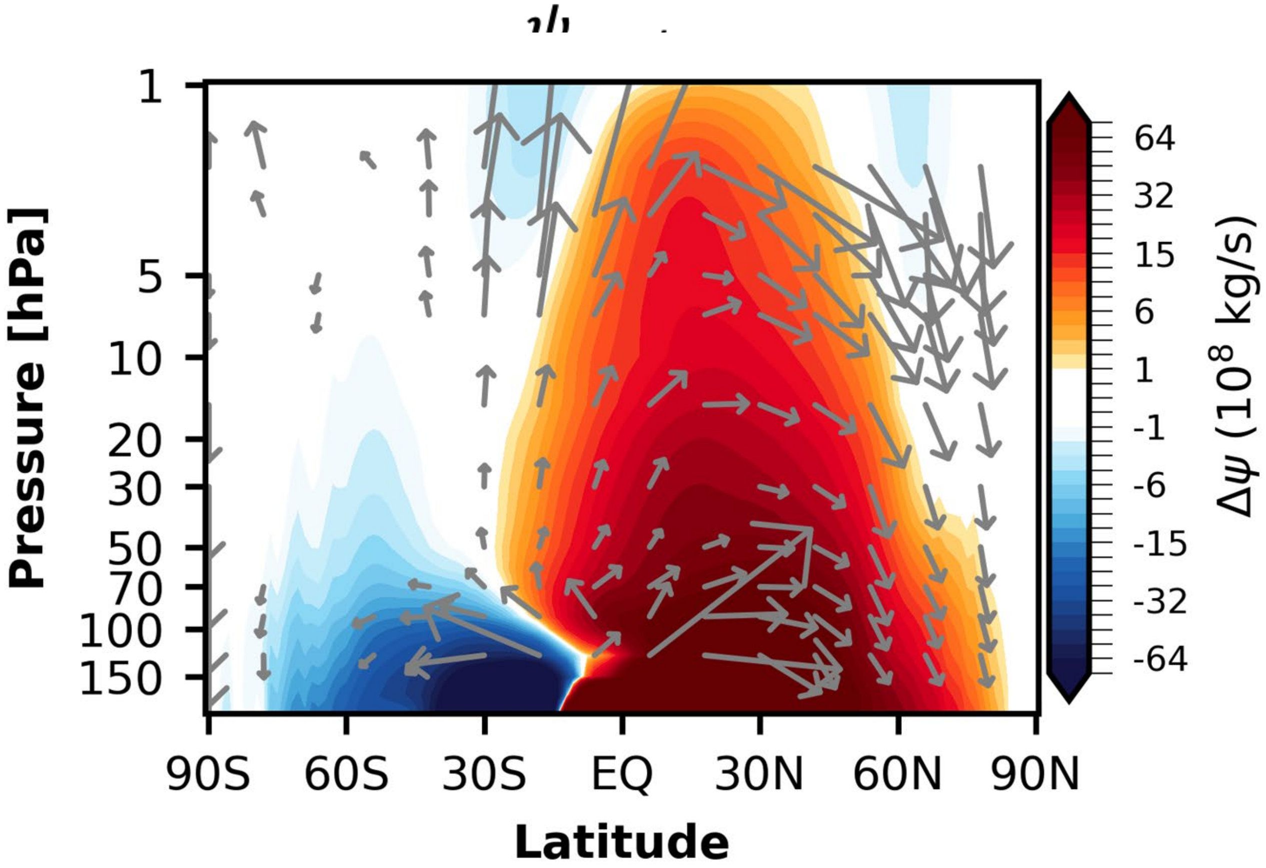
Color shading: O3

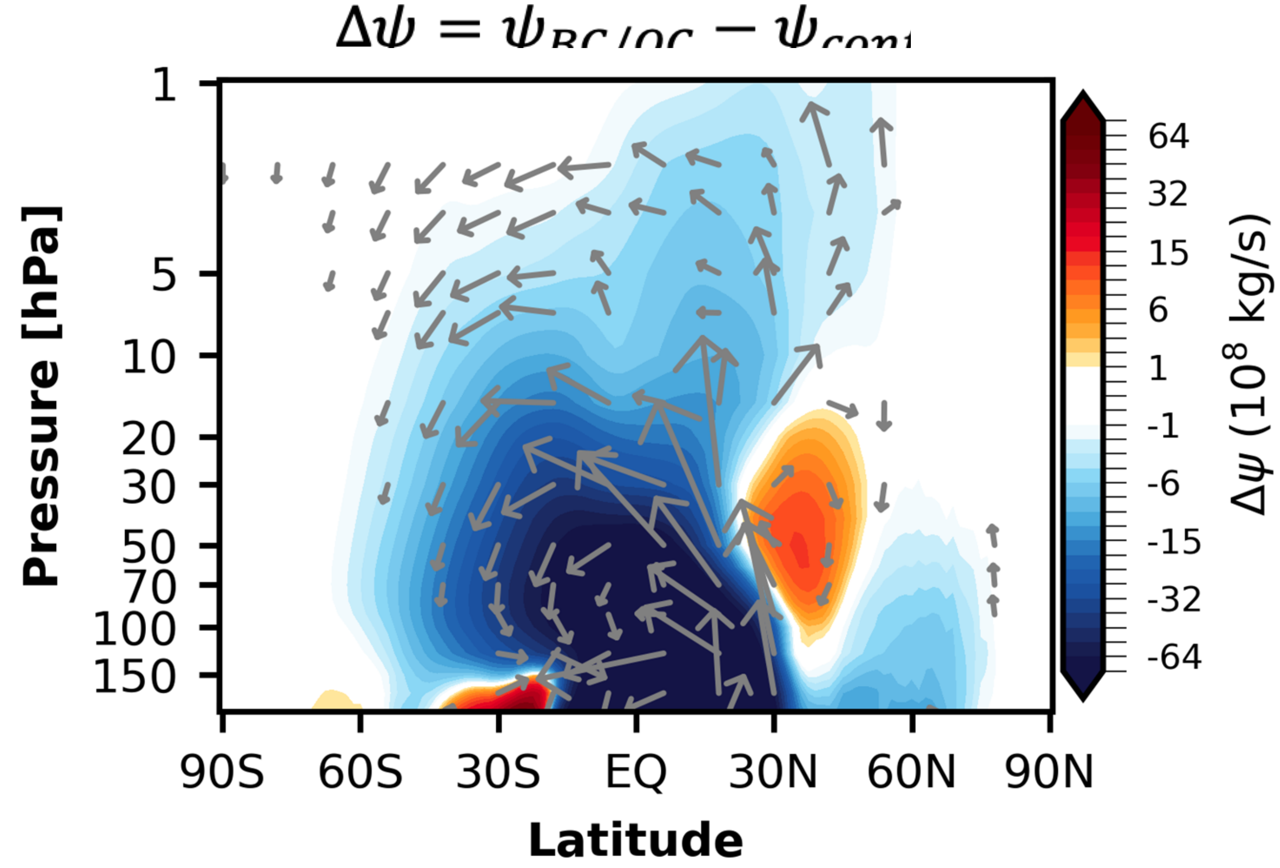


Vectors: TEM velocity (Lagrangian trajectory; residual circulation)
Color shading: O3

Transient Circulation Anomalies (January)

Transformed Eulerian Mean mass-stream function
(residual circulation)

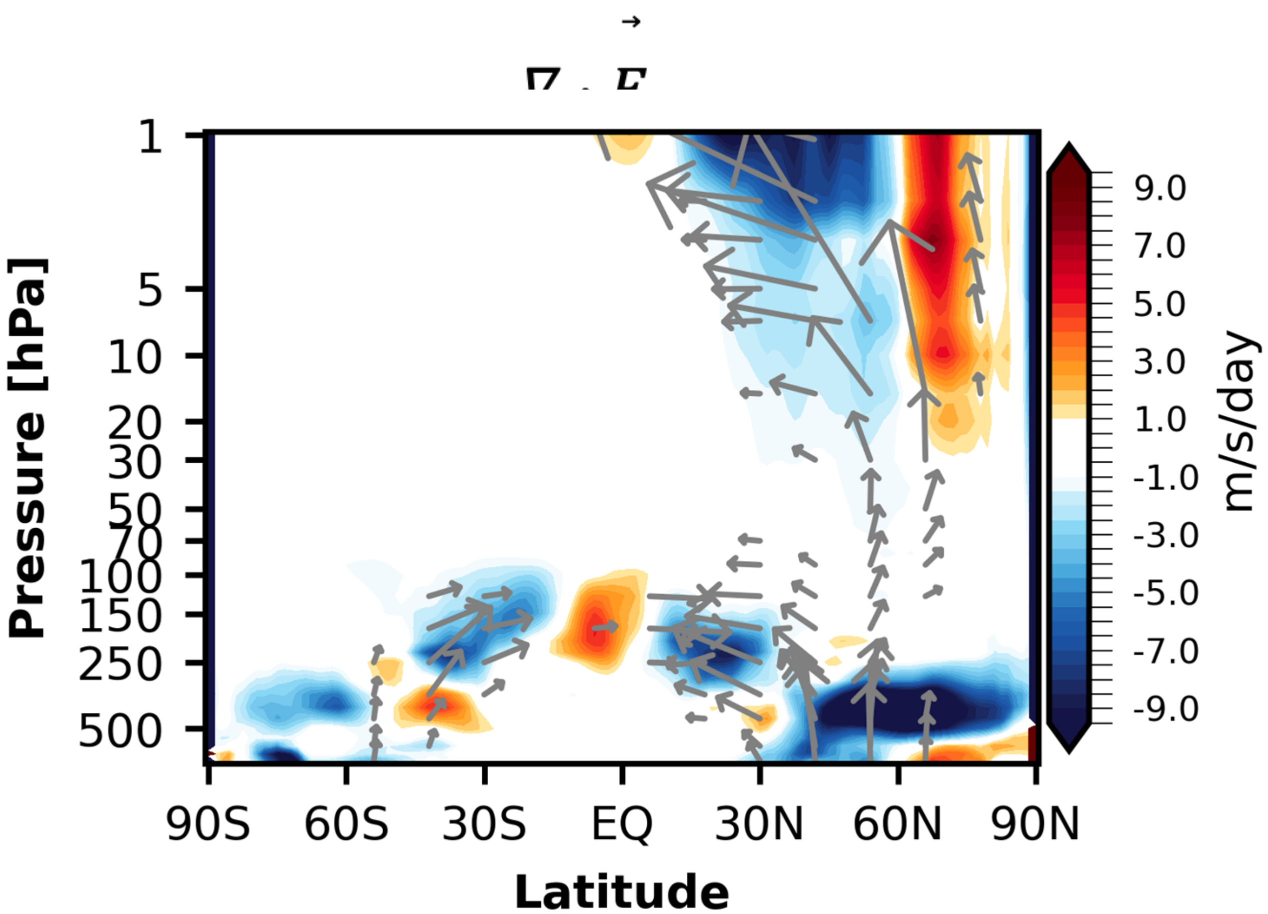


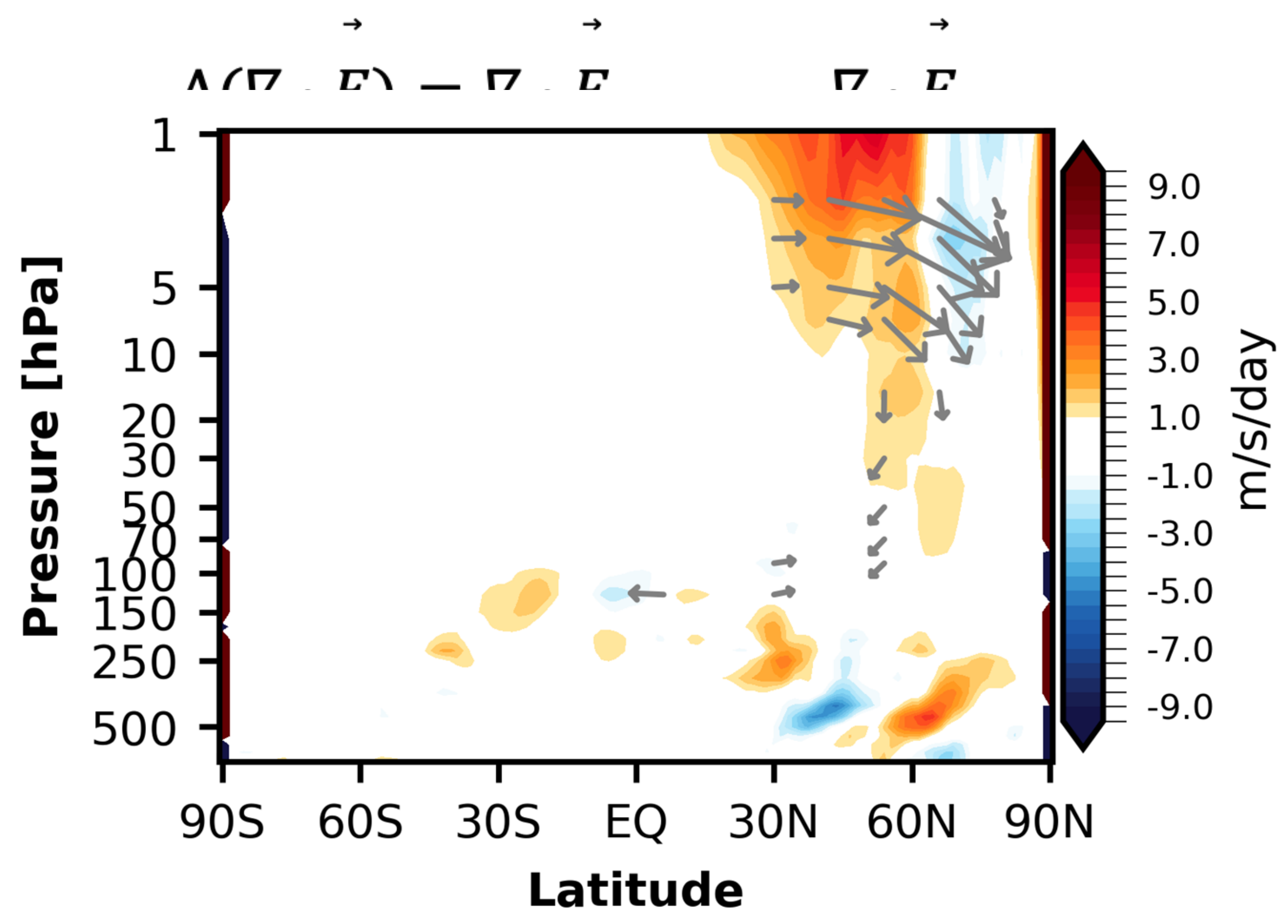


Slowing down of the Brewer-Dobson circulation
(tropical upwelling / extratropical sinking)

Transient Circulation Anomalies (January)

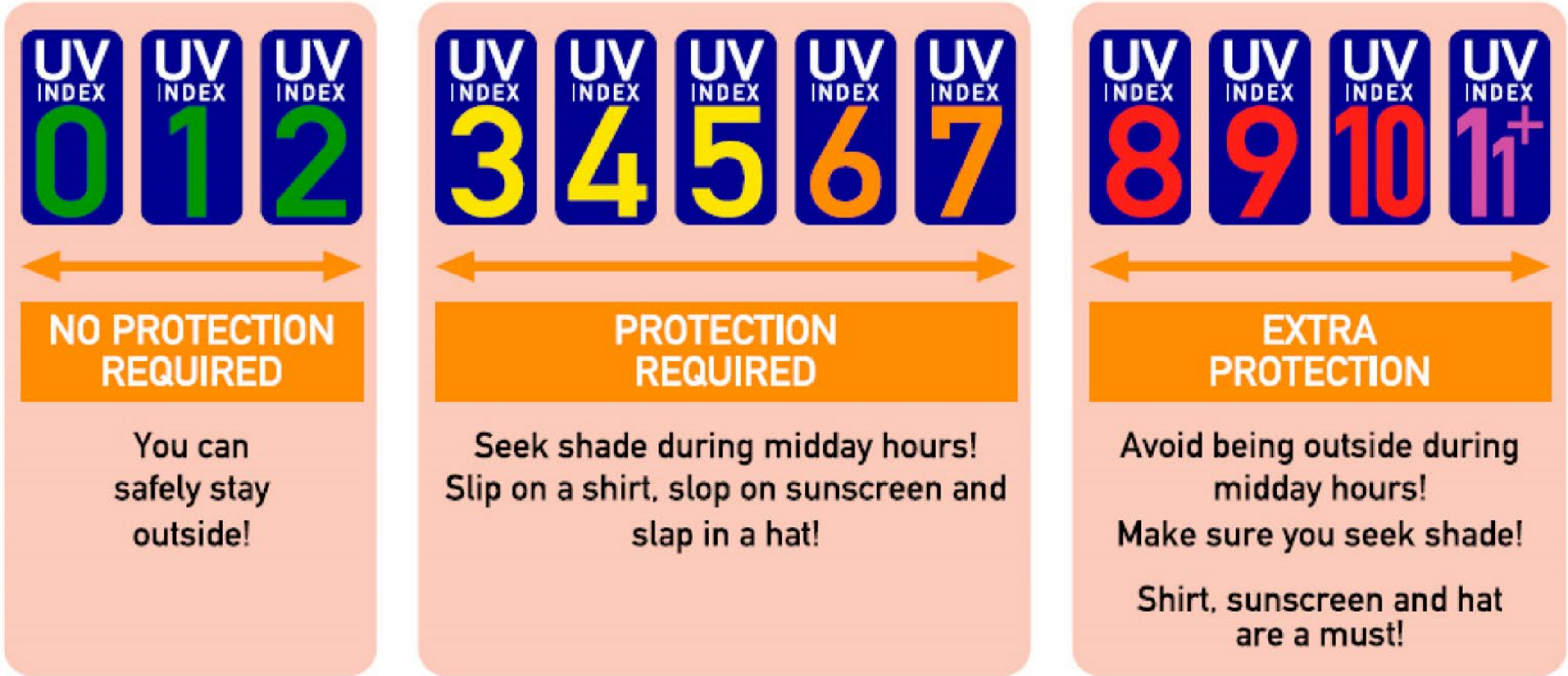
EP flux
(Planetary wave forcing)

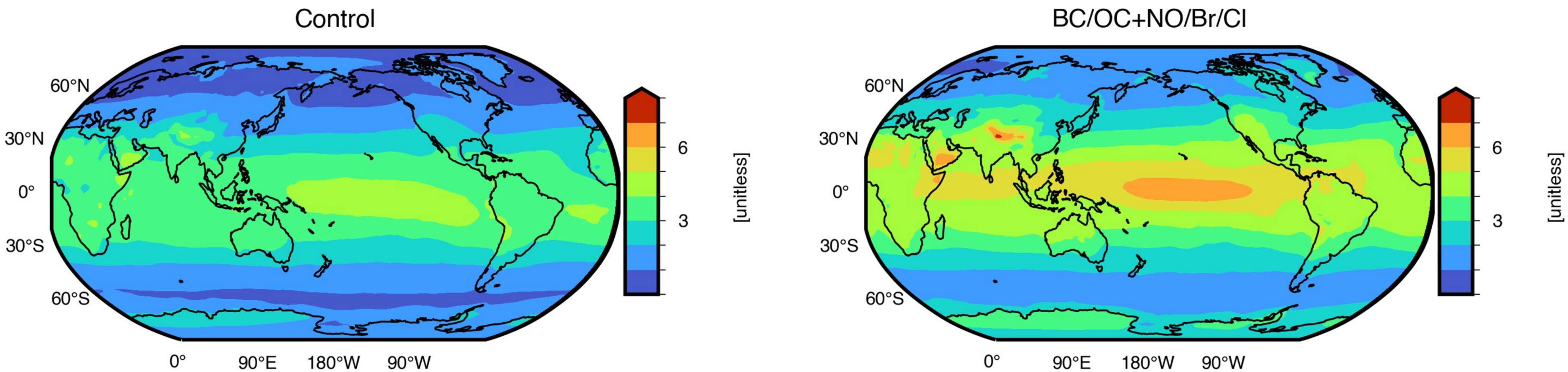




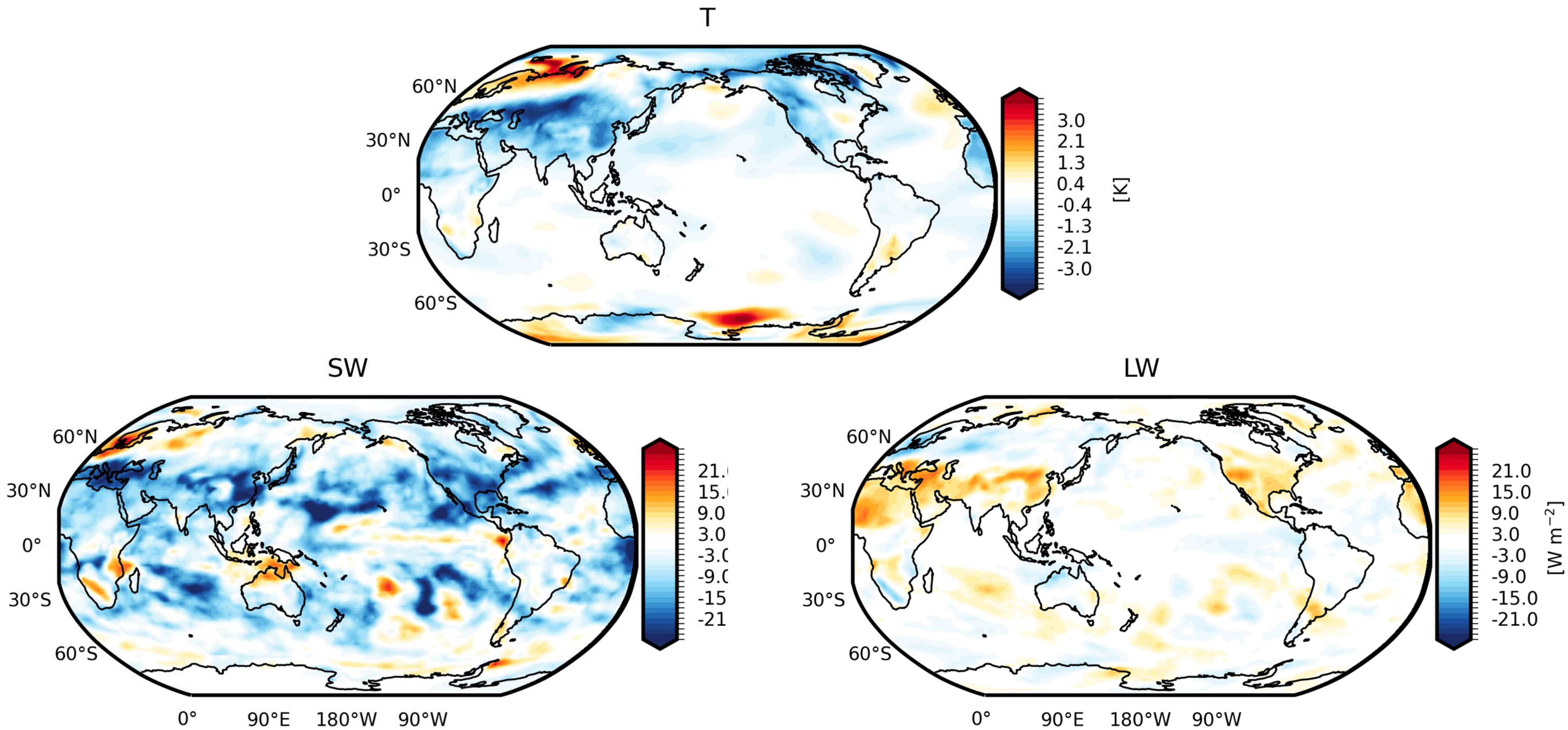
Reduced wave driving in the stratosphere

Annual mean UV-Index (WMO/WHO)



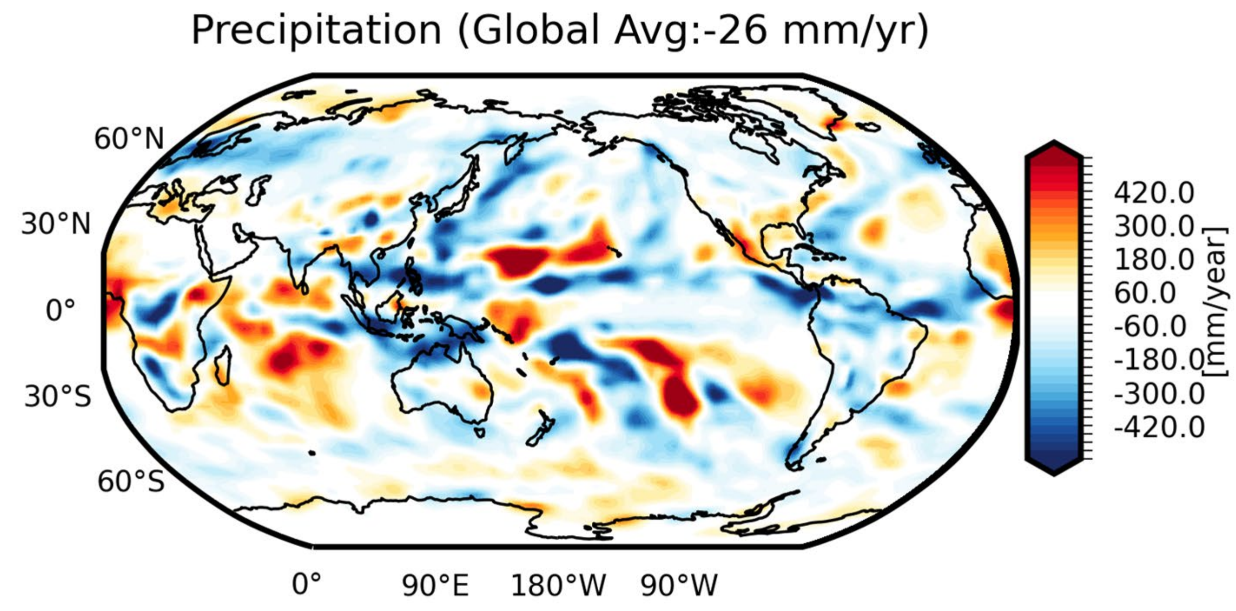


Surface Temperature Change



Radiative fluxes are defined as positive downward

Surface Precipitation Change



Global temperature and ozone change