Improved Representation of Aerosol–Photolysis Interactions in CESM Using Inline TUVx:

Implications for Ozone Loss and Surface UV After the Mount Pinatubo Eruption

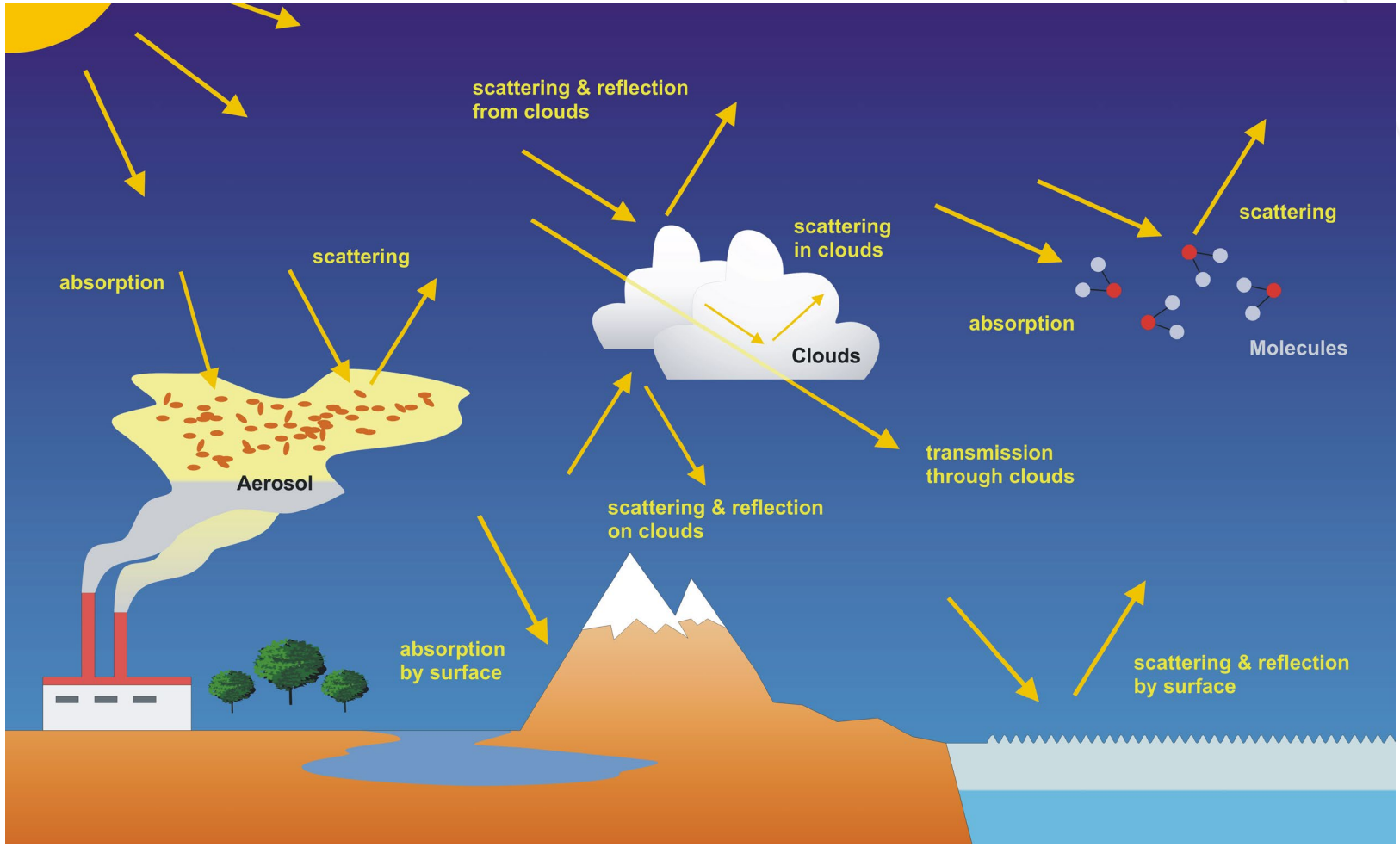
Jun Zhang

Doug Kinnison, Simone Tilmes, Francis Vitt, Ilaria Quaglia, Louisa Emmons, Matt Dawson, Stacy Walters, Kyle Shore and others

Atmospheric Chemistry Observations & Modeling Laboratory, NCAR, Boulder, CO

This material is based upon work supported by the NSF National Center for Atmospheric Research, a major facility sponsored by the U.S. National Science Foundation and managed by the University Corporation for Atmospheric Research. Any opinions, findings and conclusions or recommendations expressed in this material do not necessarily reflect the views of NSF.

Aerosol–Photolysis interactions in atmospheric chemistry



Photodissociation/photolysis processes play a key role in atmospheric photochemistry. It initiates important cycles of the chemical composition change both in the middle atmosphere and the troposphere.

Credit: DLR-IMF

CESM WACCM photolysis scheme

Photolysis coefficient: $J_x(p) = \sum_{\lambda} \sigma(\lambda) \times \phi(\lambda) \times F_{exo}(\lambda) \times N_{flux}(p, \lambda)$

$\sigma(\lambda) \times \phi(\lambda)$ is wavelength-dependent molecular absorption cross sections (σ) and quantum yields (ϕ).

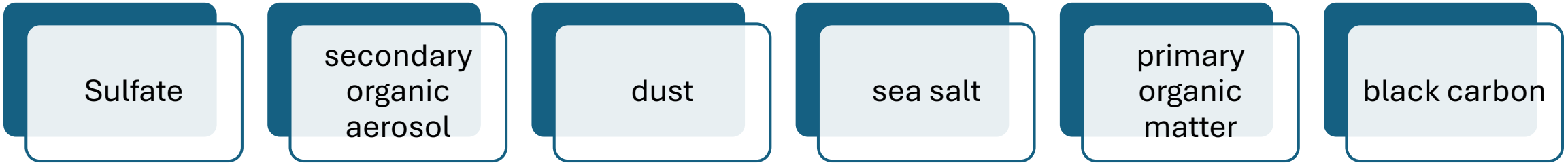
F_{exo}: top-of-atmosphere / incident λ dependent radiation (modified by Earth-Sun distance and solar cycle).

$N_{flux}(p, \lambda)$ is in-atmosphere flux after attenuation. It is a function of pressure, column O_3, SZA, Albedo…….

Lookup Table (LUT) scheme - old approach	**Inline TUVx scheme - new approach**
Offline calculation of **$N_{flux}(p, \lambda)$** using a photolysis calculator TUV	Online (inline) calculation of **$N_{flux}(p, \lambda)$** within CESM
Assumes a fixed mid-latitude O_3 vertical profile	Uses real-time modeled O_3 vertical profiles
Photolysis rates scaled by total column ozone	Photolysis rates respond dynamically to evolving atmospheric state
Aerosols effects not included	**Explicitly accounts for aerosol optical properties**
Static lookup table (LUT); no feedback with chemistry or dynamics	Fully coupled with model chemistry and aerosols, enabling interactive feedbacks

The original Tropospheric Ultraviolet and Visible (TUV) Radiation Model 5.4 source code and data sets can be found here: https://www2.acom.ucar.edu/modeling/tuv-download (Sasha Madronich).

Aerosol–Photolysis Interactions in inline TUVx CESM



Each aerosol type has different optical properties:

- **Extinction optical depth**: how much light is attenuated (scattered or absorbed) by aerosols.
- **Single scattering albedo**: the ratio of aerosol light scattering to aerosol light extinction (scattering + absorption).
- **Asymmetry parameter**: the directional preference of light scattering by aerosol.

Other aerosols?

Inline Biologically Active Irradiances in CESM (TUVx)

CESM now computes a **comprehensive suite of biologically active dose rates inline**, fully coupled to ozone and aerosols (~30 dose-rate diagnostics available).

Spectral & broadband irradiances

- UV-A, UV-B
- Visible+ and photosynthetically active radiation PAR (400–700 nm)
- Narrowband channels (e.g., 305, 320, 340, 380 nm)

Biological & health action spectra

- DNA damage 
- Plant damage & growth 
- Phytoplankton inhibition 
- Human erythema & UV Index 
- Cataract formation 
- Vitamin-D synthesis 
- Occupational exposure limits 

LUT vs Inline TUVx: Pinatubo Case Study in CESM/WACCM

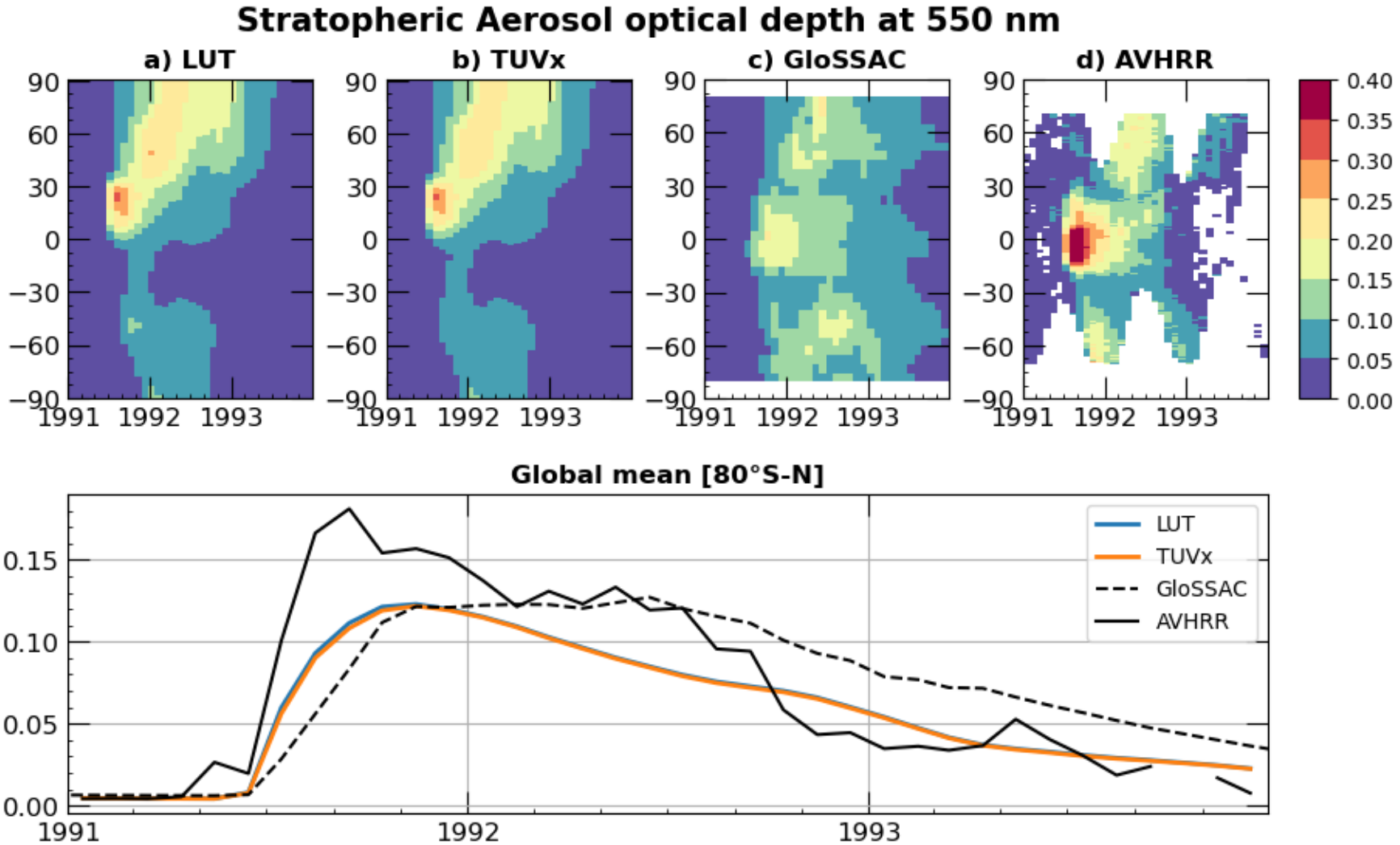
4 simulations in total:

Photolysis scheme	No Pinatubo	With Pinatubo
LUT	Control (LUT)	LUT + Pinatubo
TUVx	Control (TUVx)	TUVx + Pinatubo

Model: WACCM (nudged to MERRA2 dynamics).
Setup: 6-year spin-up (1985–1990).

Comparison:
LUT (Control vs. Pinatubo)
TUVx (Control vs. Pinatubo)
Note: All dynamics and initial conditions are identical. Differences can be directly attributed to the photolysis scheme.

Validation: Stratospheric AOD in TUVx and LUT

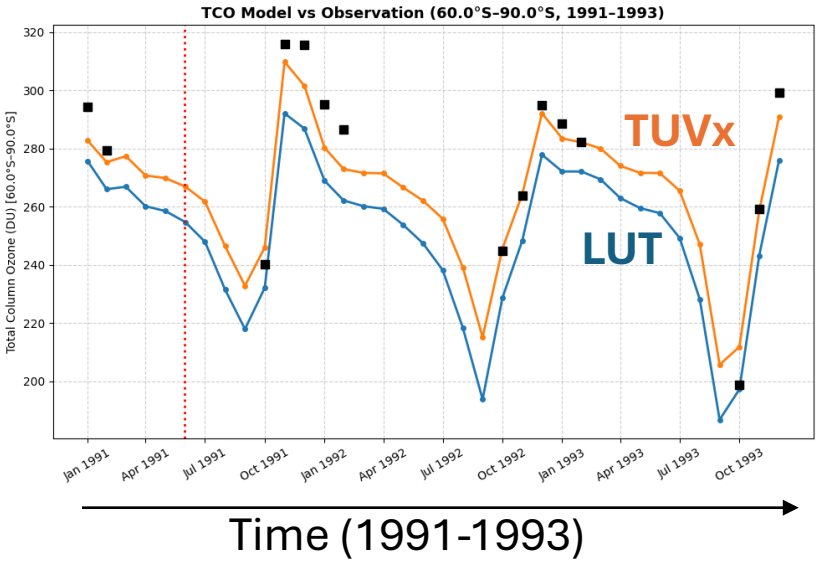


- The Global Space-based Stratospheric Aerosol Climatology (GloSSAC)
- The Advanced Very High Resolution Radiometer (AVHRR/2)
- TUVx and LUT has consistent AOD and compares well with observations.

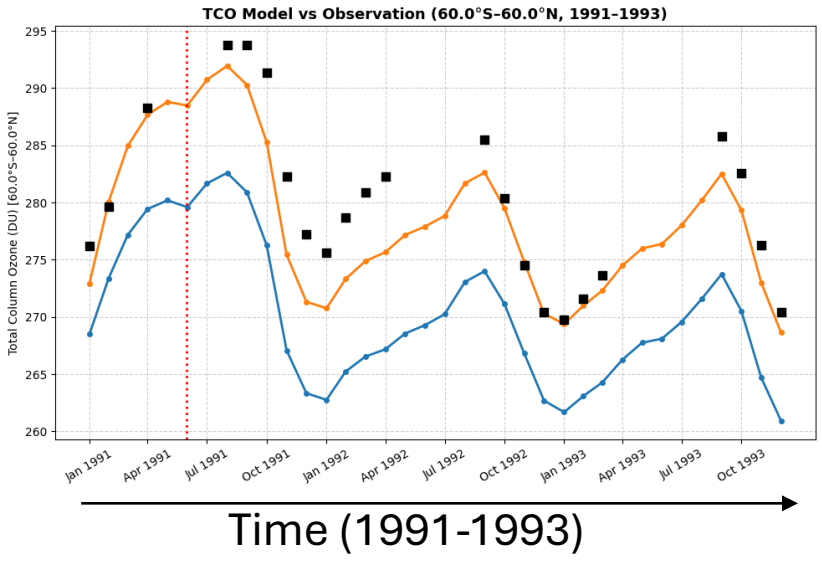
Validation: Total Column Ozone (TCO) in TUVx and LUT

SBUV Merged Ozone Data Set (MOD), 1991–1993

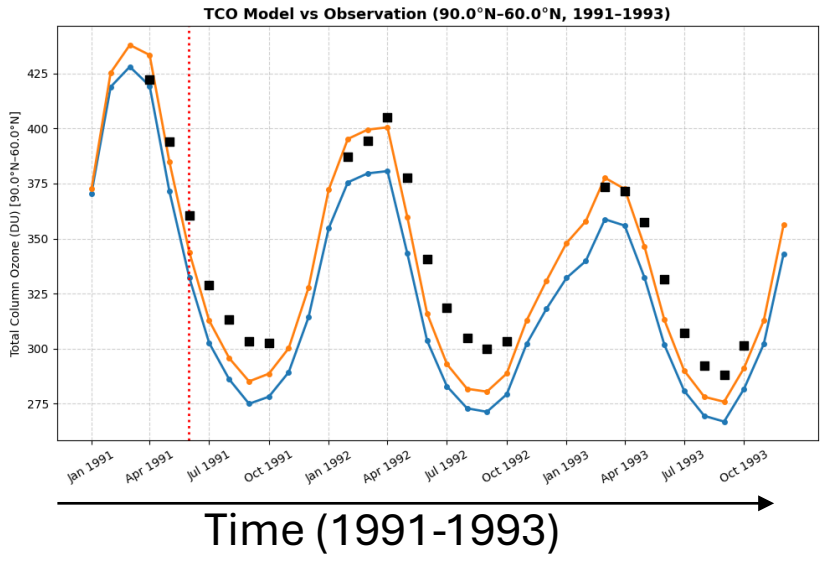
Southern cap 60S-90S



Near global 60N-60S



Northern cap 90N-60N

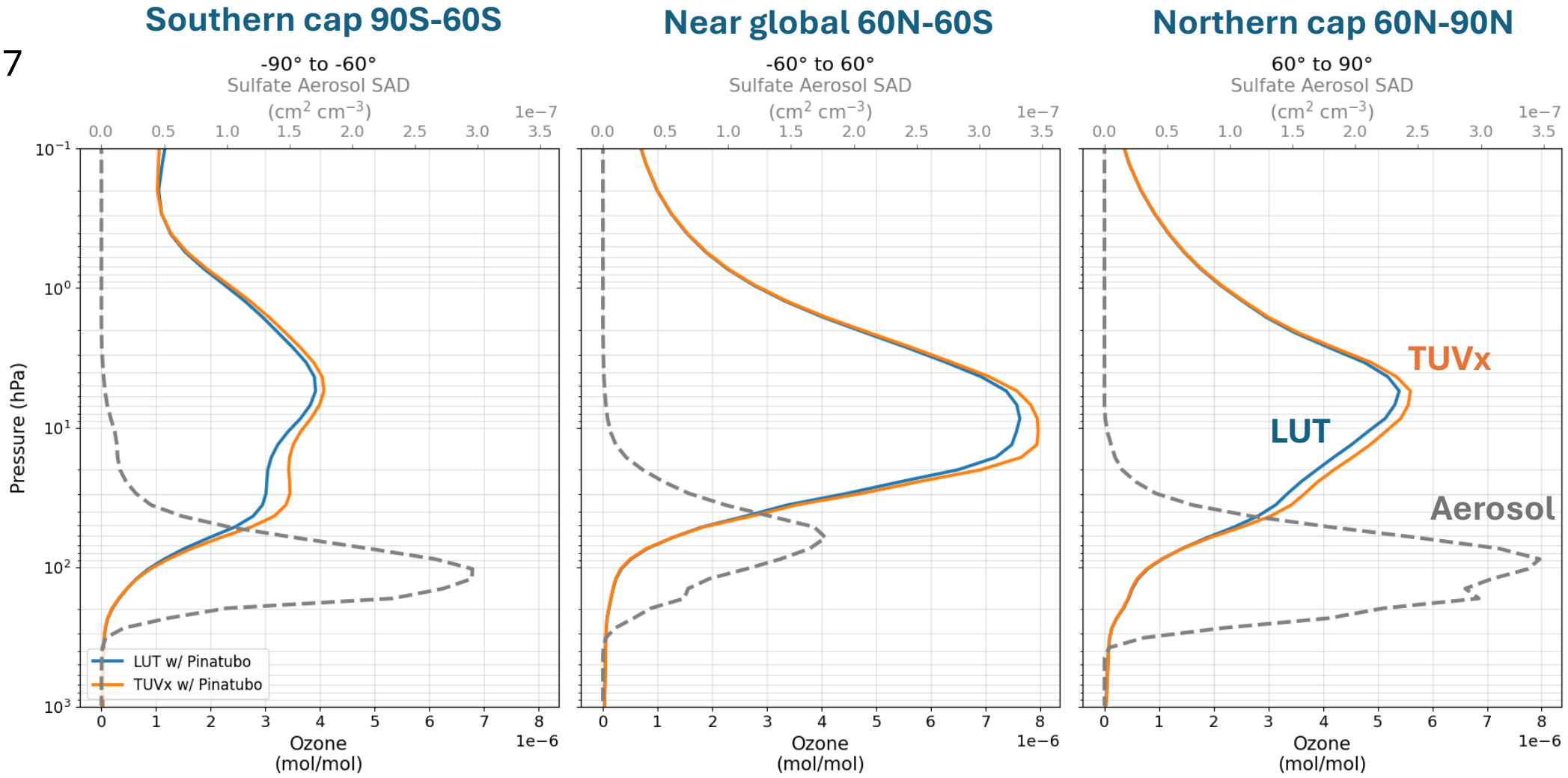


Black squares: SBUV observations
Blue line: LUT
Orange line: Inline TUVx
Red dash line: Pinatubo eruption (Jun 1991)

Inline TUVx reproduces the observed magnitude and seasonal evolution of column ozone better than LUT across the Northern polar cap, near-global region, and Southern polar cap.

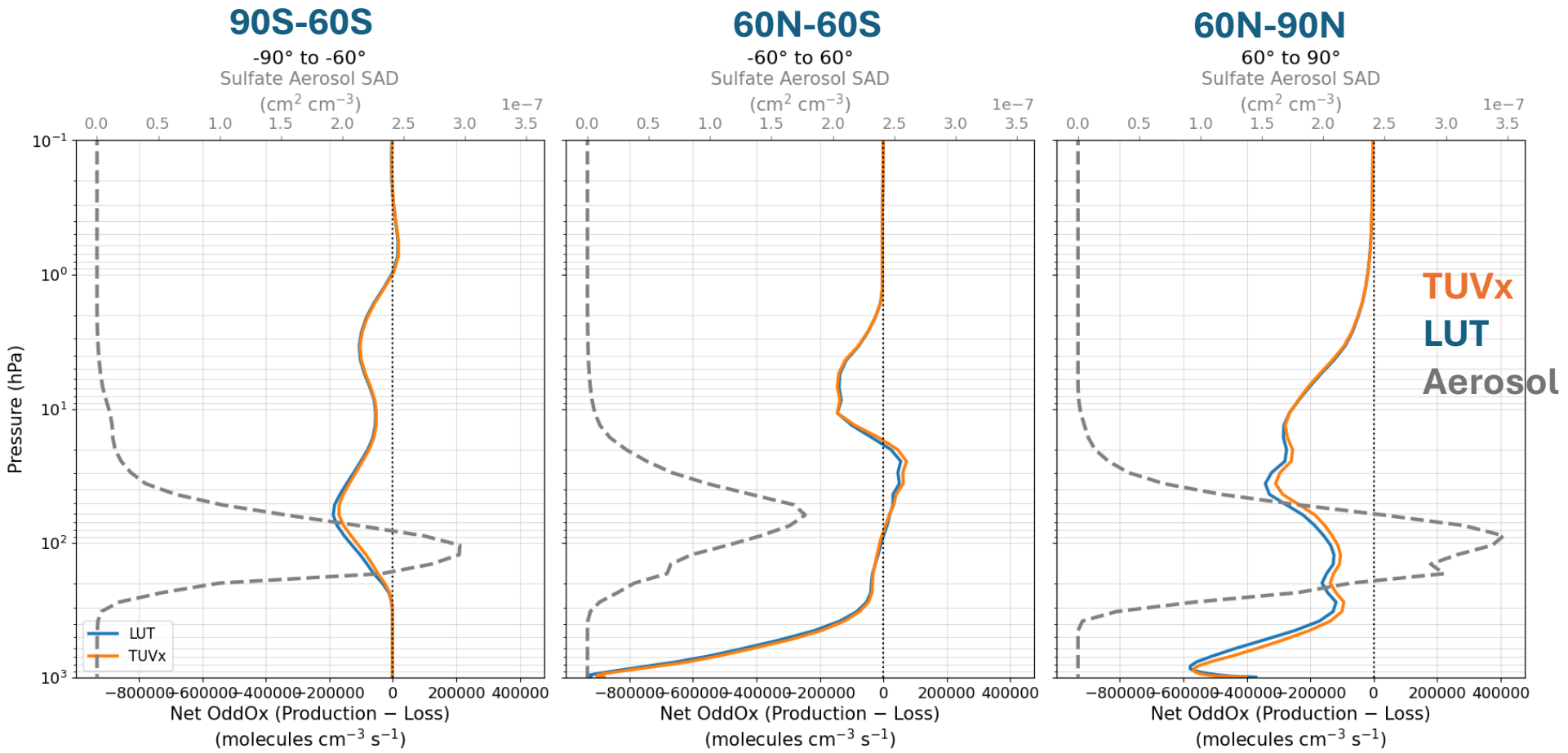
Ozone vertical profile in TUVx and LUT

1992-07



TUVx shows higher ozone concentrations above the aerosol layer compared to LUT.

Net OddOx (Production-Loss) in TUVx and LUT



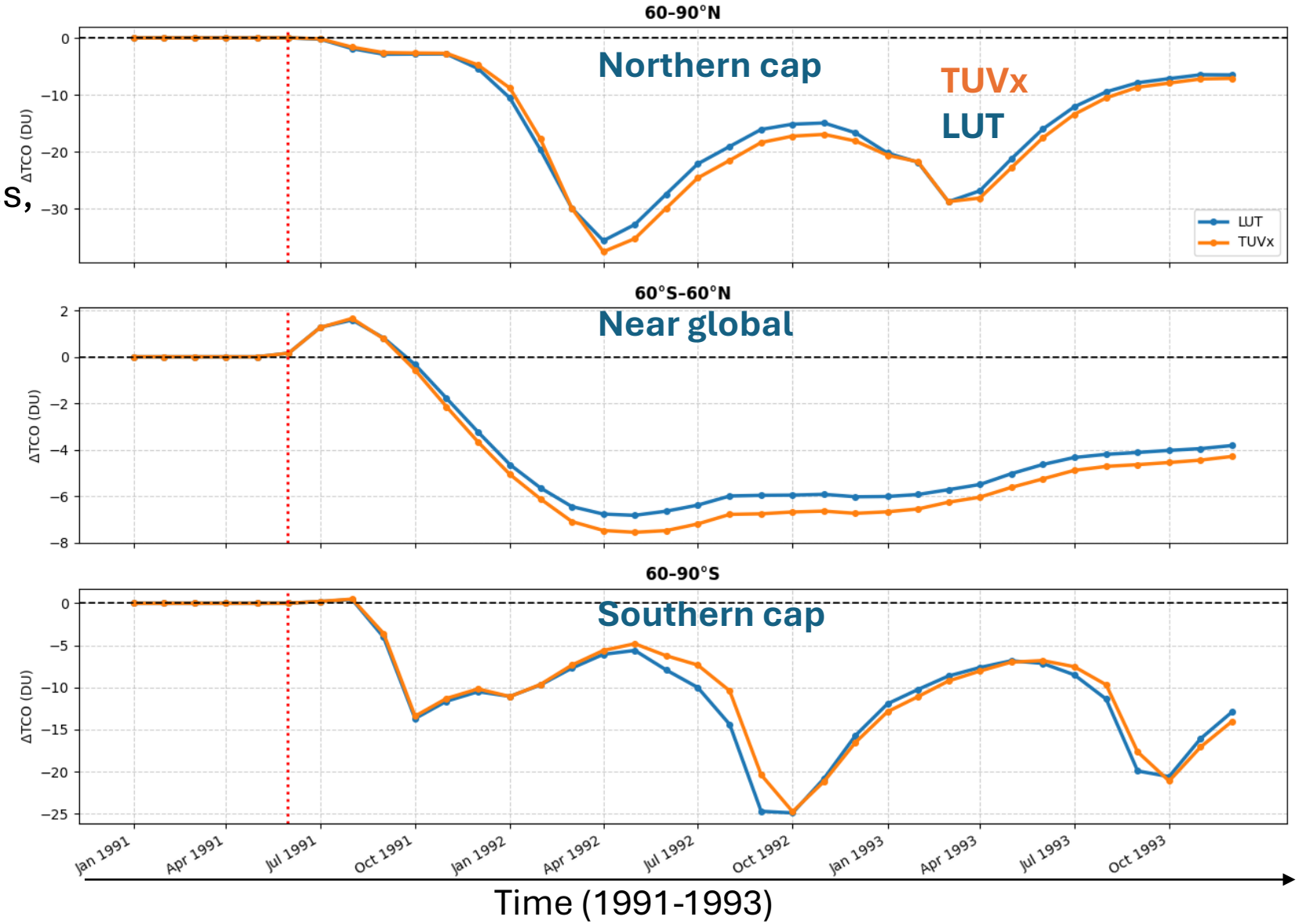
- TUVx has relatively higher net OddOx and consequently higher ozone concentrations than LUT.
- The aerosol–photolysis interactions dampen the net ozone depletion compared to the LUT method in the polar regions and enhance the ozone production over the near-global region.

Total column ozone change induced by Pinatubo injection

Pinatubo – control case

- Aerosol–photolysis interactions can modulate volcanic ozone loss, resulting in reduced ozone depletion in the Southern polar region (-20DU with TUVx versus −25DU with LUT).

- TUVx computes photolysis rates using the evolving ozone and aerosol fields. Volcanic aerosols directly perturb the vertical distribution of actinic flux and ozone chemistry. In the LUT approach, these feedbacks are largely absent.

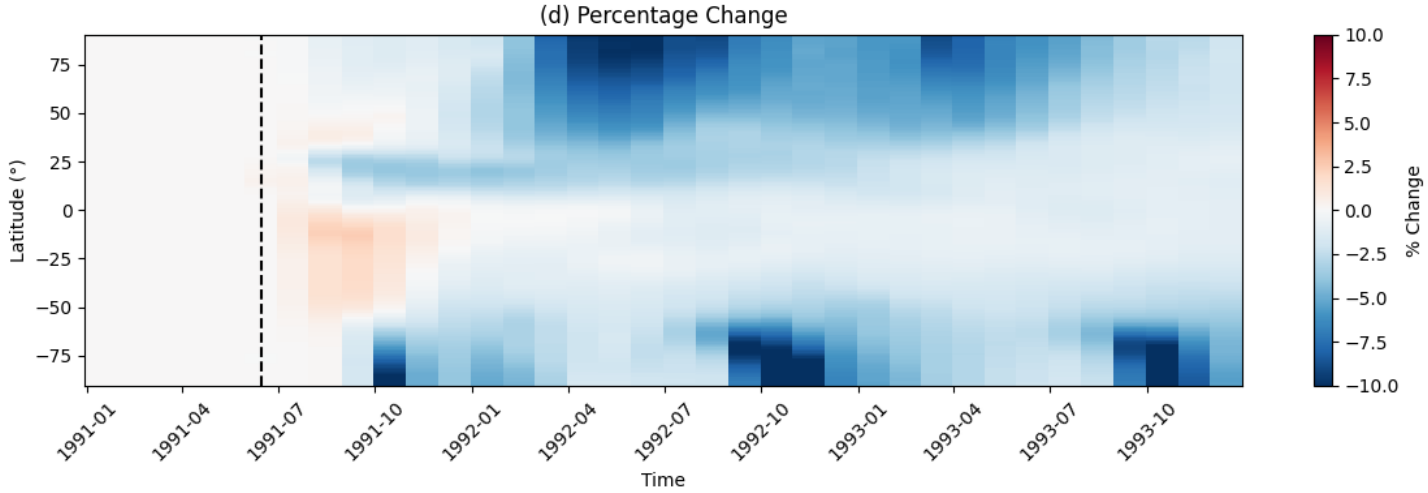


Pinatubo induced TCO and UV index change in TUVx

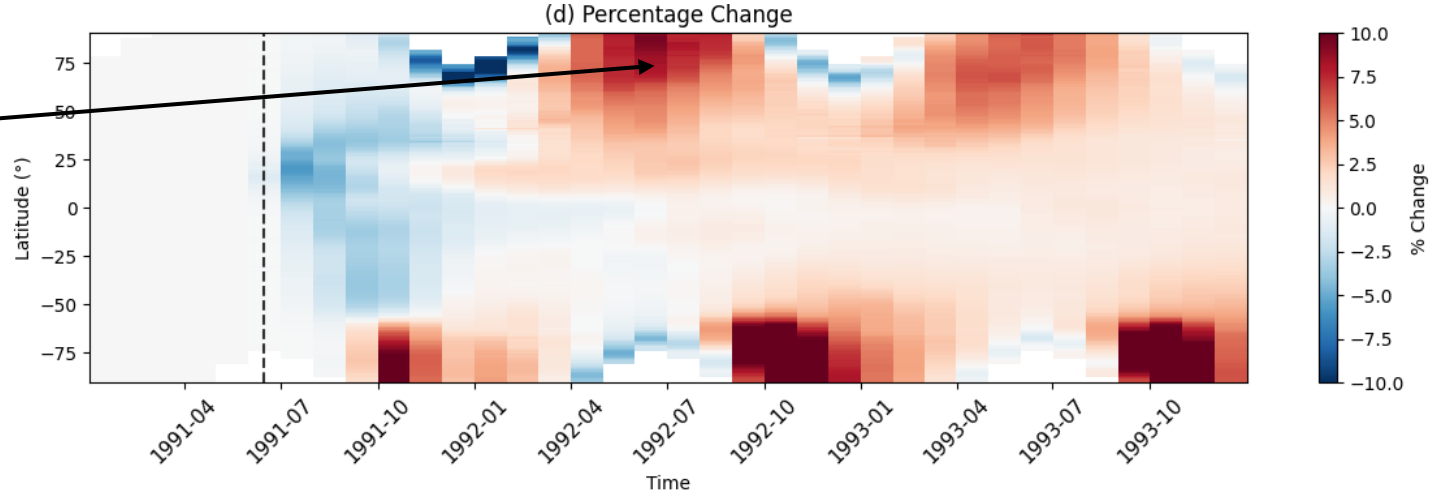
- High UV index enhancement corresponds to high ozone loss.
- Strong effects are at NH and SH mid to high latitudes during summer months.

The inline TUV-x simulation indicates that the Pinatubo eruption increased the global UV Index by up to ~10% at high latitudes during summer 1992.

Seasonal TCO % change



Seasonal UV index % change



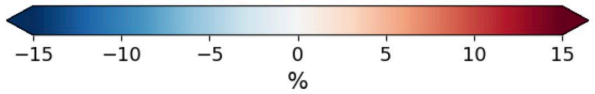
Pinatubo induced TCO change and health impact

1992-07

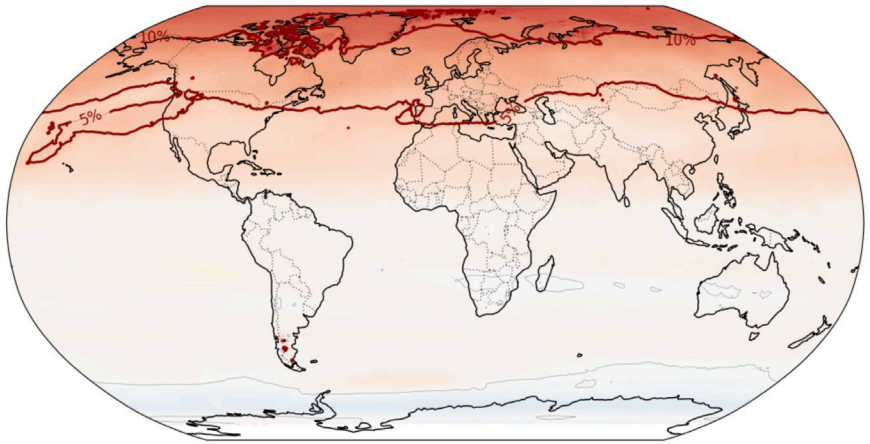
Total Column Ozone change (%)

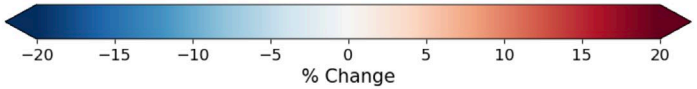
5% TCO reduction

- Corresponding increase in risk of Erythema by more than 5% and DNA damage by 10% in northern Europe and Canada.

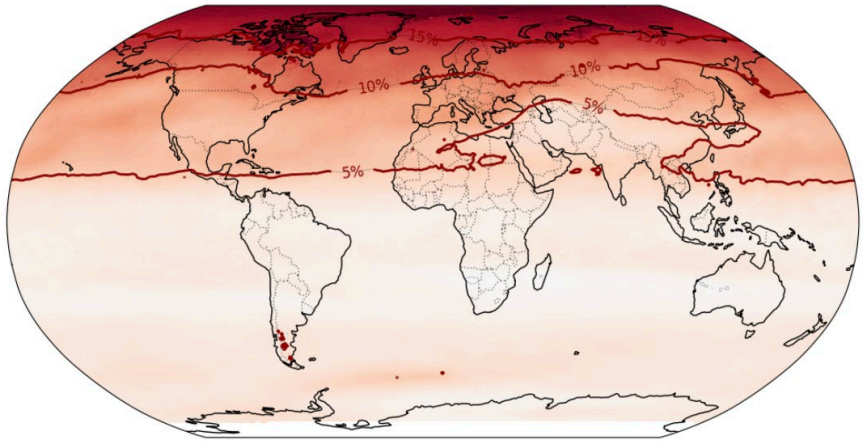


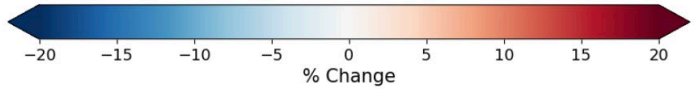
Δ Erythema (%)





Δ DNA damage (%)





Summary

•The **inline TUV-x photolysis scheme** has been successfully implemented in CESM, enabling **fully coupled, online calculations of photolysis rates** that respond to real-time changes in ozone and aerosols.

•With inline TUV-x, CESM can directly compute **biologically active ultraviolet radiation**, including diagnostics relevant to **ecosystems and human health**.

•A Pinatubo case study demonstrates that aerosol–photolysis interactions can modulate volcanic ozone loss, resulting in reduced ozone depletion in the Southern polar region (−20DU with TUV-x versus −25DU with LUT).

•The inline TUV-x simulation indicates that the Pinatubo eruption increased the global UV Index by up to ~10% at high latitudes during summer 1992, increasing erythema risk by more than 5% and DNA damage by up to 10% in northern Europe and Canada.

Proper representation of aerosol–photolysis interactions is also critical for other applications, including air quality studies (e.g., radiative dimming below aerosol layers) and Stratospheric Aerosol Injection assessments.

Odd Ox production and loss profile

1992-07

- Both the production and loss rates of odd oxygen (Ox) are enhanced in TUVx.
- Aerosol layer increases upward scattering of radiation, leading to enhanced actinic flux above the aerosol layer.

OddOx production

OddOx loss (all loss cycles)