UKESM General Assembly

Science Talks – Session A

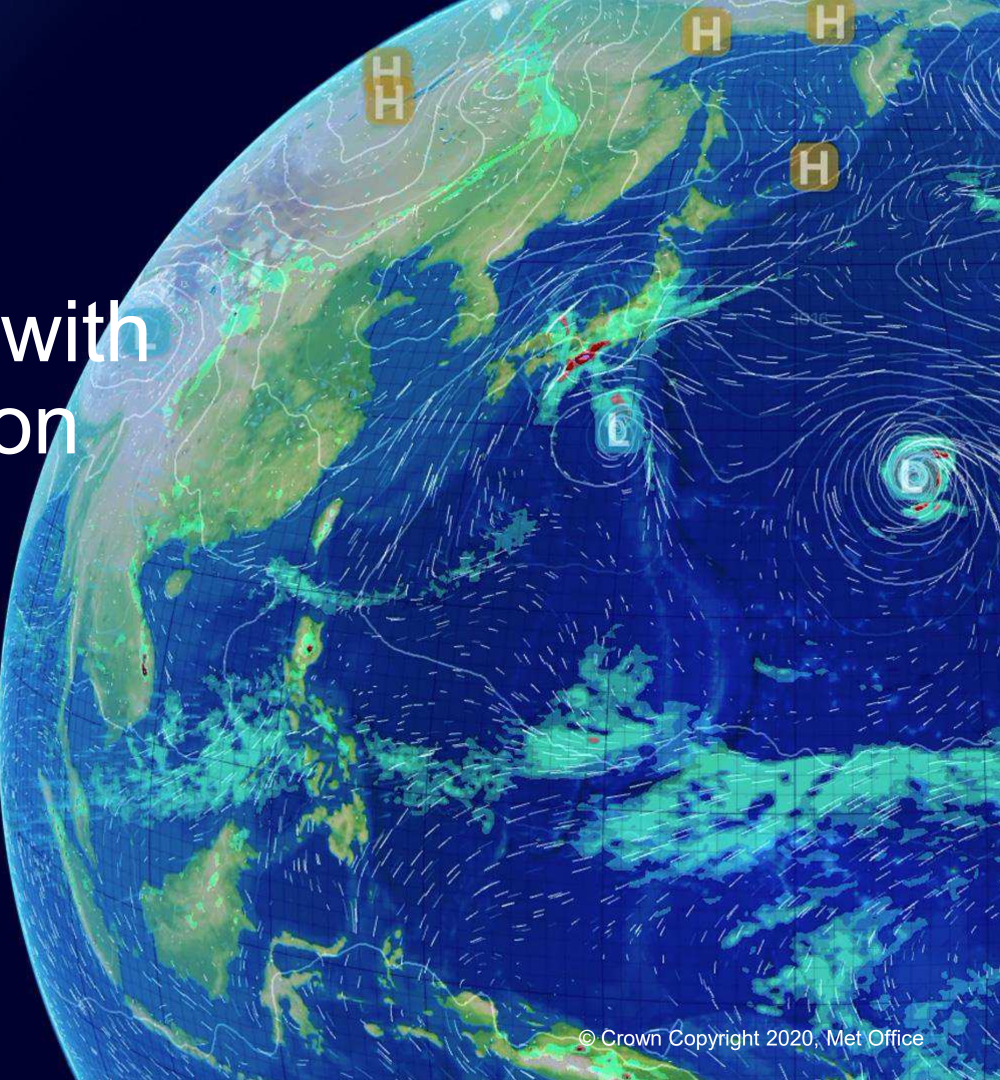
Catherine Hardacre

Met Office

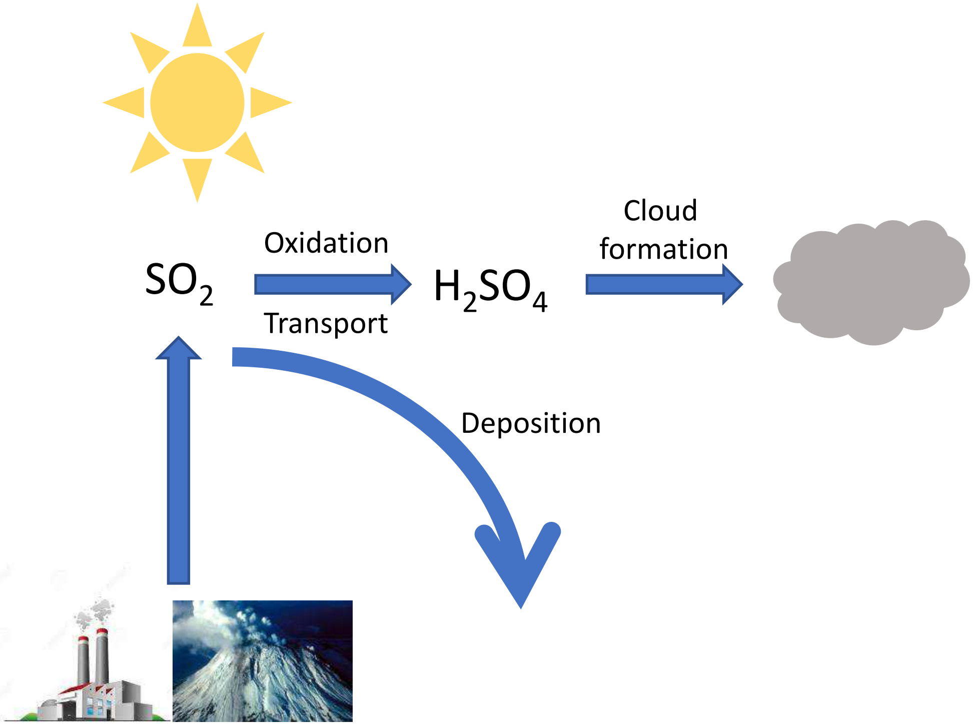
Met Office

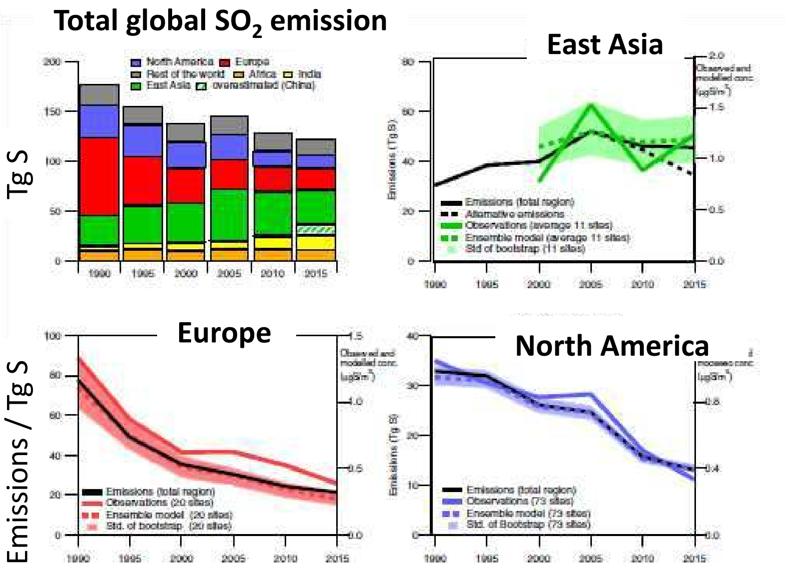
Challenging UKESM1 with observations: Evaluation of sulphur species

Catherine Hardacre, Jane Mulcahy, Steve Rumbold, Colin Johnson, Richard Pope and Colin Jones



Background: Sulphur species in the atmosphere

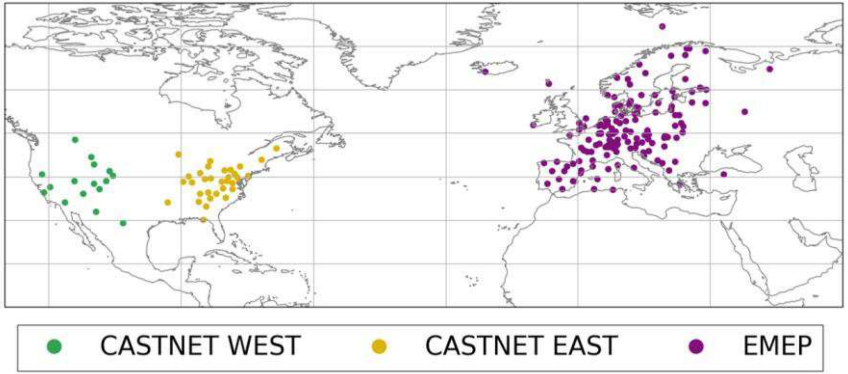




From: Aas et al., Nature/Scientific Reports (2019) https://doi.org/10.1038/s41598-018-37304-0

Observational and model data sets

Surface measurements networks used in this study



CASTNET = Clean Air Status and Trends Network
- ~1987 – present, [SO_2], [SO_4^{2-}] , SO_2 dry deposition
- https://www.epa.gov/castnet

EMEP = Environmental Monitoring and Evaluation Program
- ~1979 – present, [SO_2], [SO_4^{2-}]
- https://www.eea.europa.eu//themes/air/dc

UKESM1 set up

- Four members of the CMIP6 historical ensemble*
- Fully coupled model with Strat-Trop chemistry** and GLOMAP aerosol†
- Data from ~1987 – 2014
- Surface SO_2 and SO_4^{2-} concentrations, and SO_2 dry deposition

* Sellar, et al. (2019). UKESM1: Description and evaluation of the U.K. Earth System Model. *Journal of Advances in Modeling Earth Systems*, 11, 4513– 4558.

** Archibald, et al., (2020) *Description and evaluation of the UKCA stratosphere–troposphere chemistry scheme (StratTrop vn 1.0) implemented in UKESM1.* Geoscientific Model Development, 13 (3). pp. 1223-1266. ISSN 1991-959X

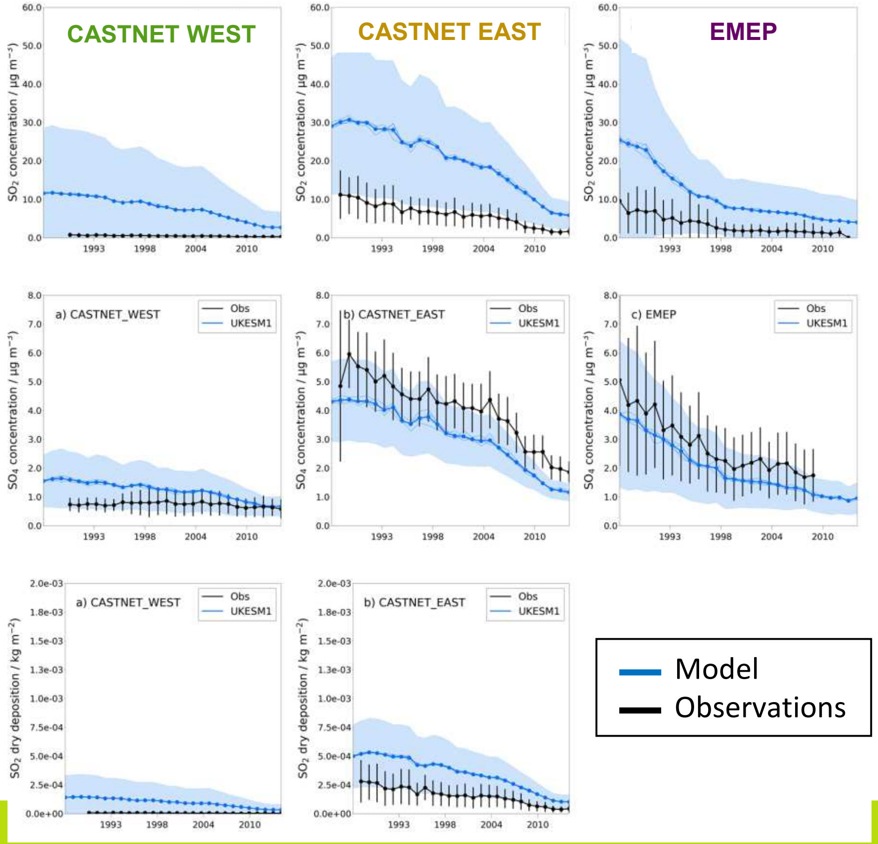
† Mulcahy, et al. (2018). Improved aerosol processes and effective radiative forcing in HadGEM3 and UKESM1. *Journal of Advances in Modeling Earth Systems*, 10, 2786– 2805.

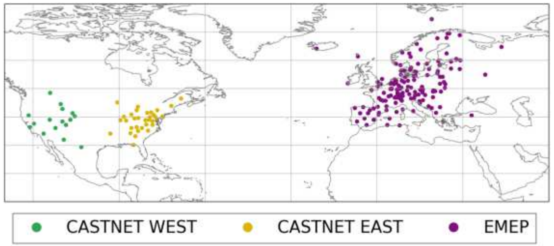
Trends in sulphur species

SO_2 concentration ($\mu g\ m^{-3}$)

SO_4^{2-} concentration ($\mu g\ m^{-3}$)

SO_2 dry deposition ($kg\ m^{-2}$)





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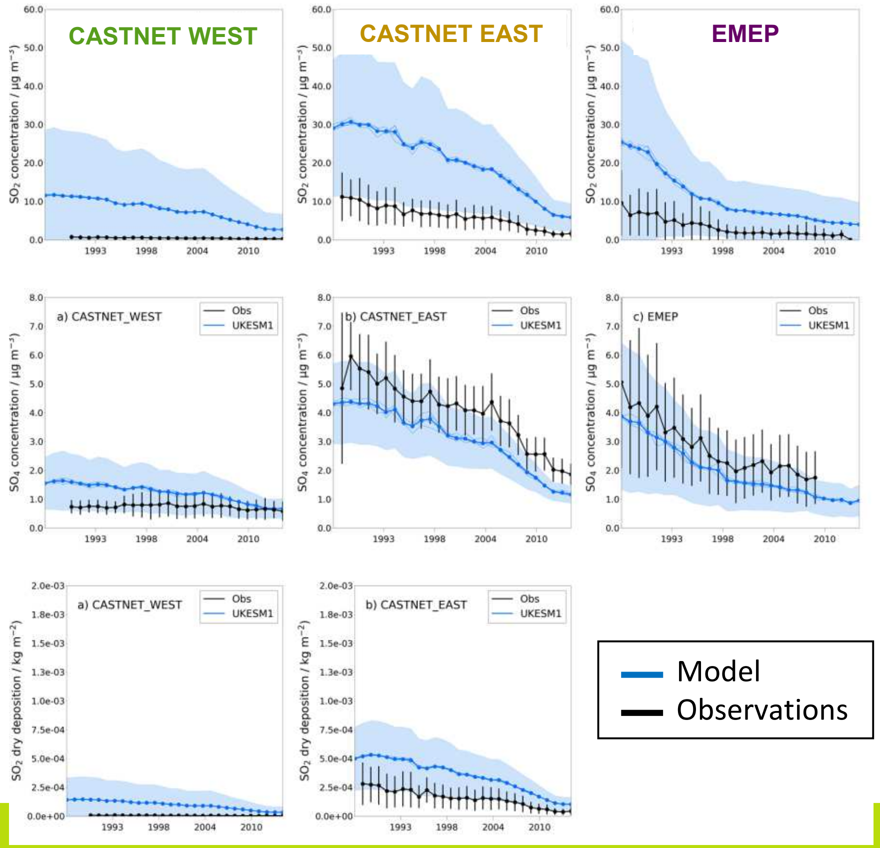
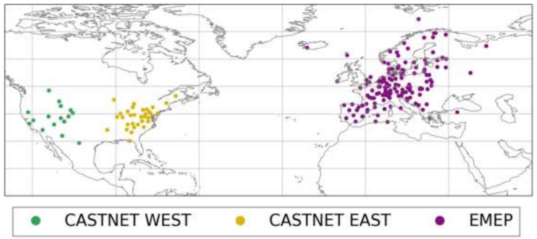


Model
Observations

UKESM captures long term trends in surface SO_2 concentration, surface SO_4^{2-} concentration and in SO_2 dry deposition, but there are biases!



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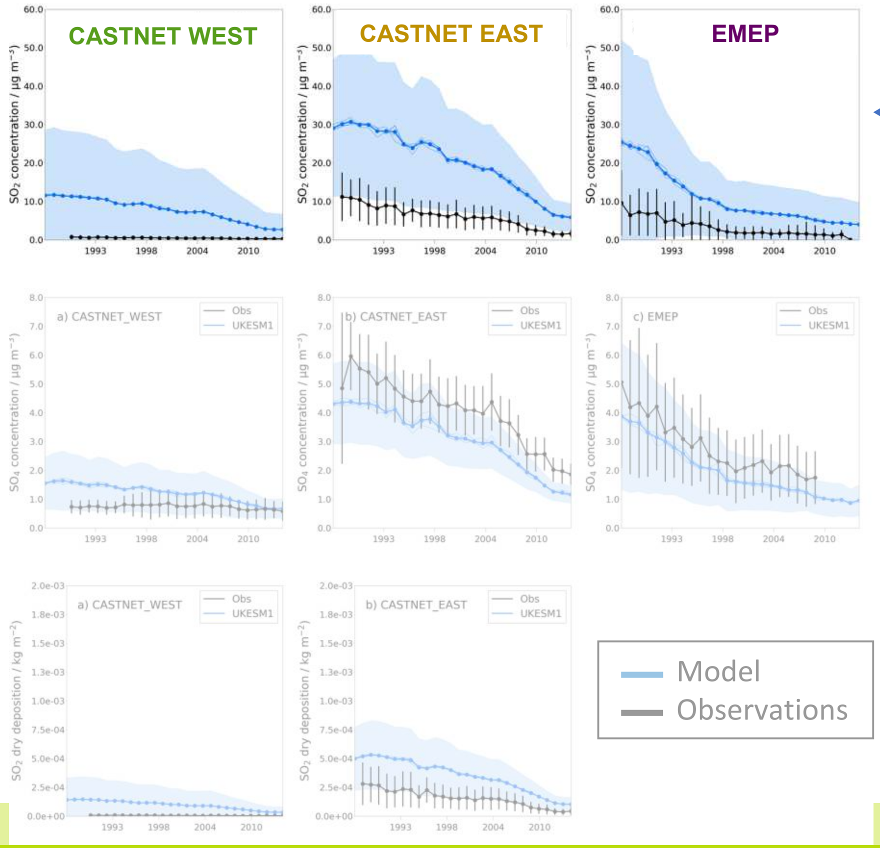
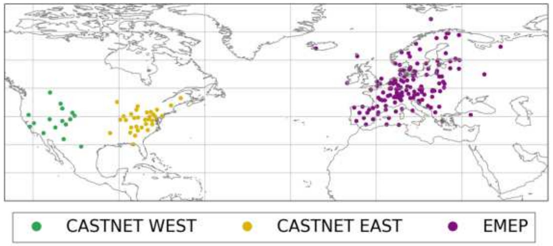


UKESM1 over predicts surface SO_2 concentrations

Model
Observations



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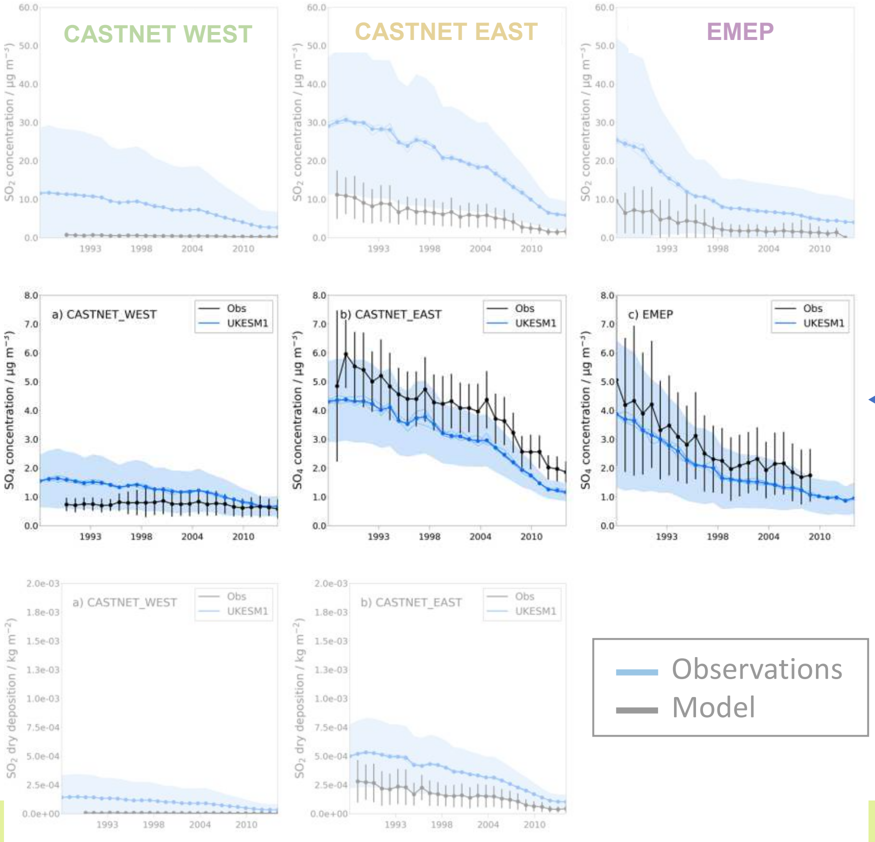
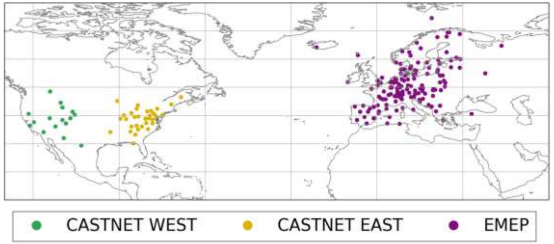


UKESM1 under predicts surface SO_4^{2-} concentrations



Trends in sulphur species

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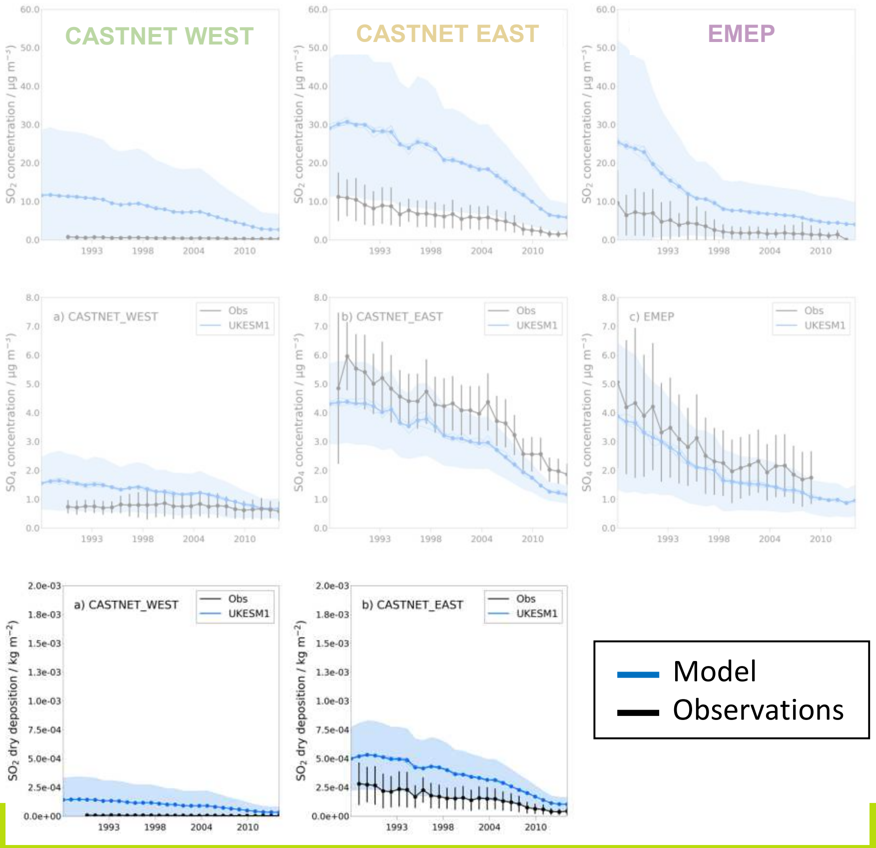
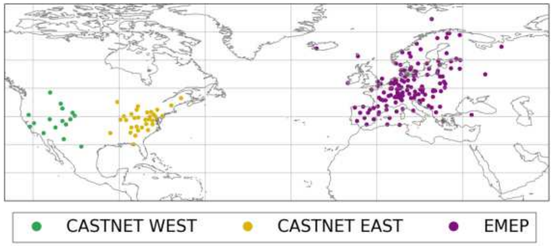


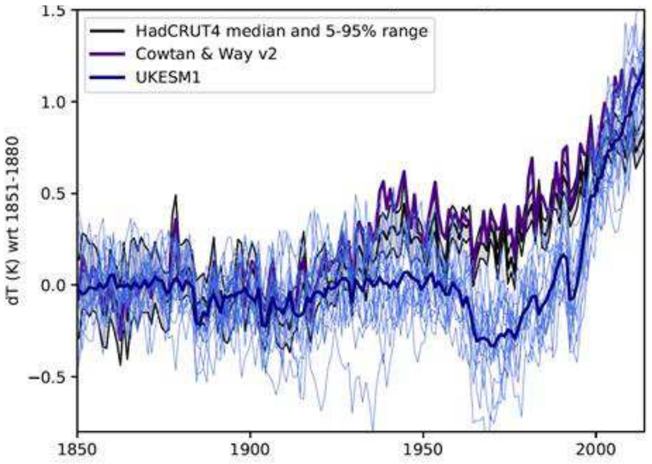
UKESM1 over predicts SO_2 dry deposition



Met Office

Development of UKESM1: improvements to the SO_2 dry deposition process

Global mean surface air temperature



Modifications and bug fixes to SO_2 dry deposition:

- Include memory of surface wetness after rainfall
- Fix the surface resistance (Rc) parameter for SO_2 dry deposition to water
- https://code.metoffice.gov.uk/trac/um/ticket/5167

Other changes include: Strat-Trop nucleation bug fix, DMSO yield fix, vegetation quasi-laminar resistance set to 1.0, zref set at 10m and HandDeB stability terms used.

Met Office

Trends in sulphur species

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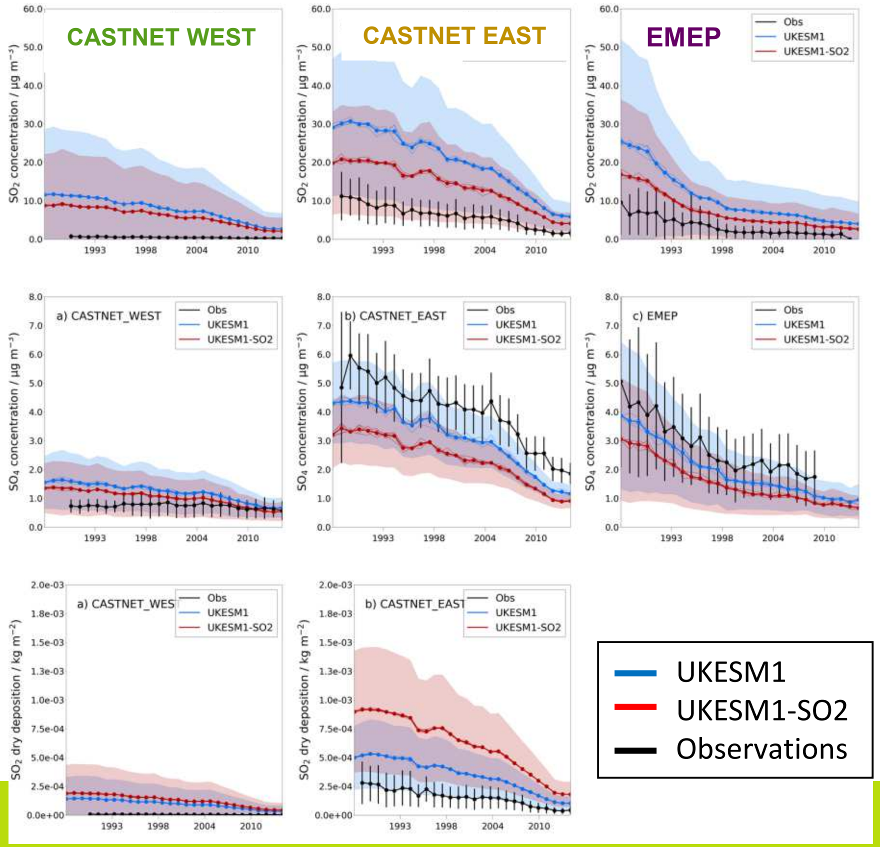
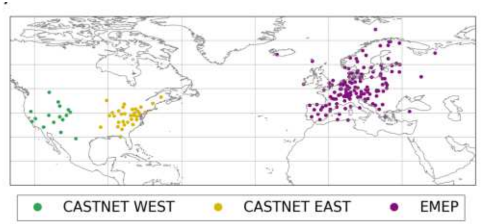
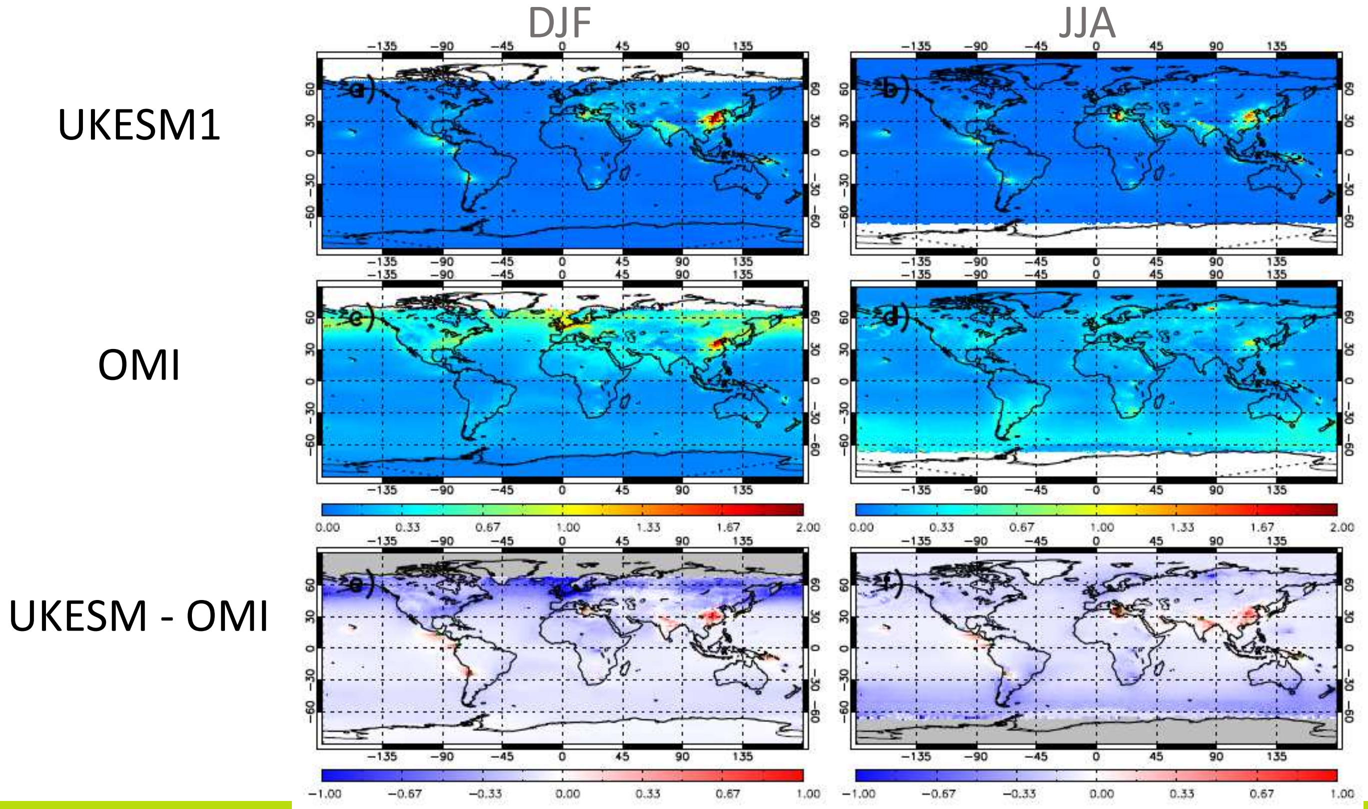
SO_4^{2-} concentration ($\mu g\ m^{-3}$)

SO_2 dry deposition ($kg\ m^{-2}$)





Initial satellite comparisons for SO_2*



* Courtesy of Richard Pope at Leeds Uni

Nicolas Bellouin

University of Reading

Department of Meteorology

University of Reading

BOUNDING GLOBAL AEROSOL RADIATIVE FORCING OF CLIMATE CHANGE

Nicolas Bellouin, Johannes Quaas, Ed Gryspeerdt, Stefan Kinne, Philip Stier, Duncan Watson-Parris, Olivier Boucher, Ken Carslaw, Matt Christensen, Anne-Laure Daniau, Jean-Louis Dufresne, Graham Feingold, Stephanie Fiedler, Piers Forster, Andrew Gettelman, Jim Haywood, Ulrike Lohmann, Florent Malavelle, Thorsten Mauritsen, Daniel McCoy, Gunnar Myhre, Johannes Muelmenstaedt, David Neubauer, Anna Possner, Maria Rugenstein, Yousuke Sato, Michael Schulz, Steve Schwartz, Odran Sourdeval, Trude Storelvmo, Velle Toll, David Winker, and Bjorn Stevens.

UKESM General Assembly Online, 17 June 2020

Approach

Identify lines of evidence that quantify:

1. Industrial-era changes in aerosol optical depth (ari) and cloud droplet number (aci)
2. Sensitivity of top-of-atmosphere radiation, atmospheric absorption, and clouds to those changes
3. Fractions of the globe where radiative forcing is exerted

Global average only, 2005-2015 with respect to 1850, 68% confidence

Table 4

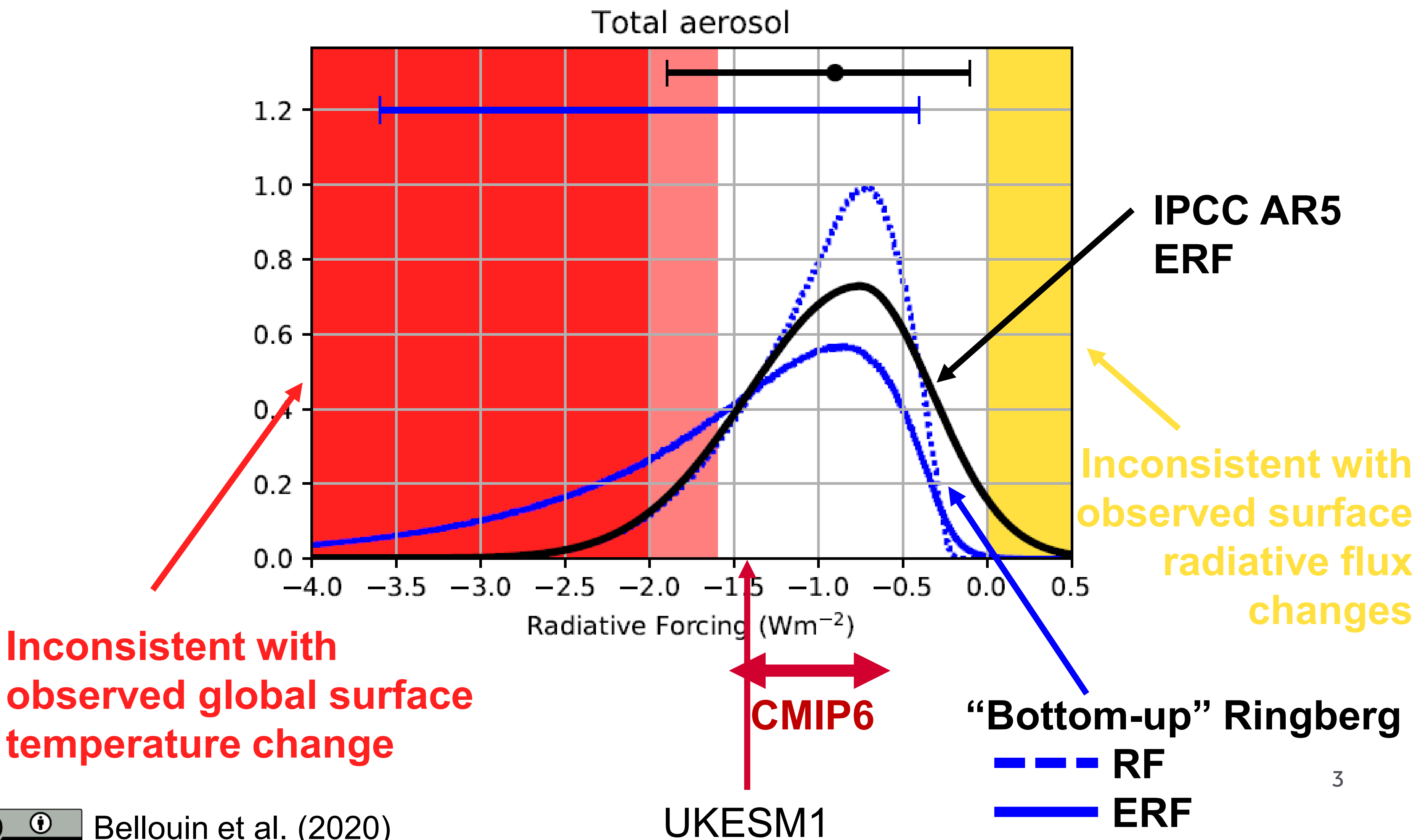
Ranges Obtained by This Review in the 16–84% Confidence Interval for the Variables of Equations (8), (15), and (24)

Section	Variable	Lower bound	Upper bound	Line of evidence
4	τ_a^{PD}	0.13	0.17	Satellite retrievals
4	$\Delta\tau_a$	0.02	0.04	Global modeling
4	$\Delta\ln\tau_a = \Delta\tau_a/\tau_a^{PD}$	0.14	0.29	Modeling/satellite
6	$\Delta\ln N_d = \Delta N_d/N_d$	0.05	0.17	Modeling/satellite
Aerosol-radiation interactions				
5	S_τ^{clear} [W m^{-2} τ_a^{-1}]	−27 (0.08)	−20 (0.06)	Global modeling
5	c_τ	0.59	0.71	Global modeling
5	S_τ^{cloudy} c_τ [W m^{-2}]	−0.1	+0.1	Global modeling
5	*RF of ari* [W m^{-2}]	*−0.37*	*−0.12*	
7	dR/dR_{atm}	−0.3	−0.1	Global modeling
7	$dR_{atm}/d\tau_a$ [W m^{-2} τ_a^{-1}]	17	35	Global modeling
7	*RA of ari* [W m^{-2}]	*−0.25*	*−0.06*	
7	*ERF of ari* [W m^{-2}]	*−0.58*	*−0.23*	
Aerosol-cloud interactions				
6	$\beta_{\ln N-\ln\tau}$	0.3	0.8	Modeling/satellite
6	S_N [W m^{-2}]	−27 (0.079)	−26 (0.076)	Satellite retrievals
6	c_N	0.19	0.29	Modeling/satellite
6	*RF of aci* [W m^{-2}]	*−1.10*	*−0.33*	
8	$\beta_{\ln\mathcal{L}-\ln N}$	−0.36	−0.011	Satellite analyses
8	$S_{\mathcal{L},N}$ [W m^{-2}]	−54	−56	Mixed
8	$c_{\mathcal{L}}$	0.21	0.29	Mixed
8	*RA of aci (liquid water path)* [W m^{-2}]	*0.01*	*+0.56*	
8	$\beta_{C-\ln N}$	0	0.1	Global modeling, LES
8	$S_{C,N}$ [W m^{-2}]	−91	−153	Satellite analysis
8	c_C	0.59	1.07	Mixed
8	*RA of aci (cloud fraction)* [W m^{-2}]	*−1.14*	*0.0*	
8	*ERF of aci* [W m^{-2}]	*−1.73*	*−0.27*	
11	**Total aerosol ERF** [W m^{-2}]	**−2.19**	**−0.61**	
11	(constrained by observational inferences)	−1.60	−0.61	

Bellouin, N., et al. (2020). Bounding global aerosol radiative forcing of climate change. *Rev Geophys*, 58, e2019RG000660. https://doi.org/10.1029/2019RG000660

Bounding aerosol ERF

University of Reading

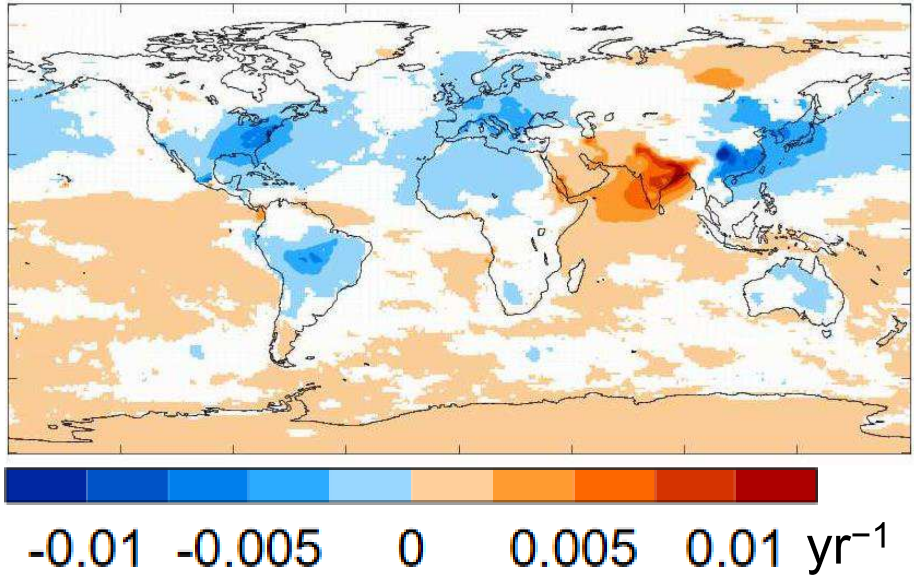


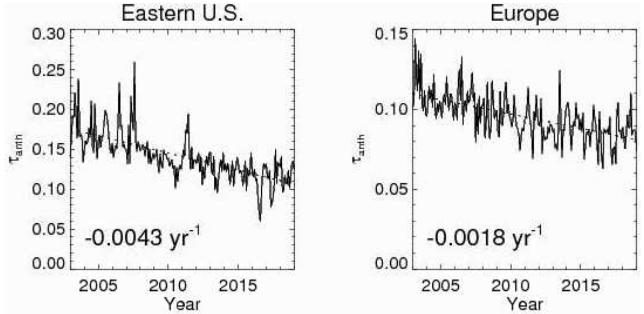
 Bellouin et al. (2020)

Promising avenues

- Scale effects are increasingly being considered in model development. Global large eddy simulation is now becoming possible.
- Cloud responses to regional aerosol trends, and volcanic eruptions and ship tracks may provide insights into cloud regime shifts and ice cloud responses.
- Observational inferences are promising but their uncertainties need to be better understood. Large regional trends (right) may provide strong constraints.
- Models of all scales involve a large number of poorly known parameters, and statistical methods to explore model uncertainties are being adopted.

Deseasonalised linear trends in anthropogenic aerosol optical depth 2003—2019, based on CAMS Reanalysis





Update to Bellouin et al. https://doi.org/10.5194/essd-2019-251

Gerd Folberth

Met Office

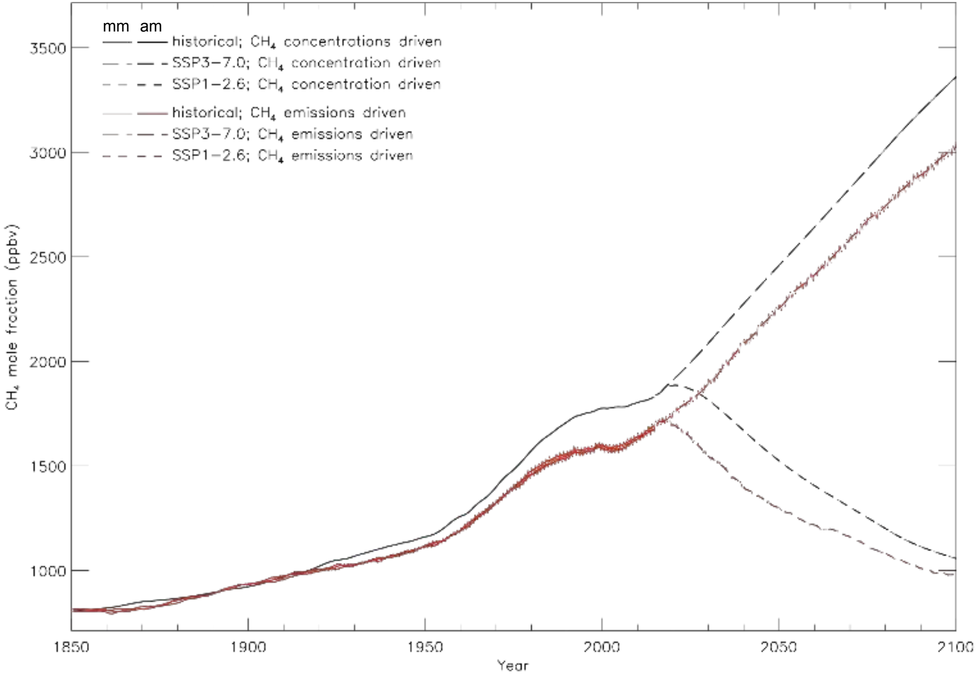
CH_4 Surface Mole Fraction – 1850 to 2100

CH_4 concentration-driven configuration
CH_4 emissions-driven configuration

$\Delta CH_4(PI \rightarrow PD)$ = ~1,100 ppbv
$\Delta CH_4(PI \rightarrow PD)$ = ~900 ppbv

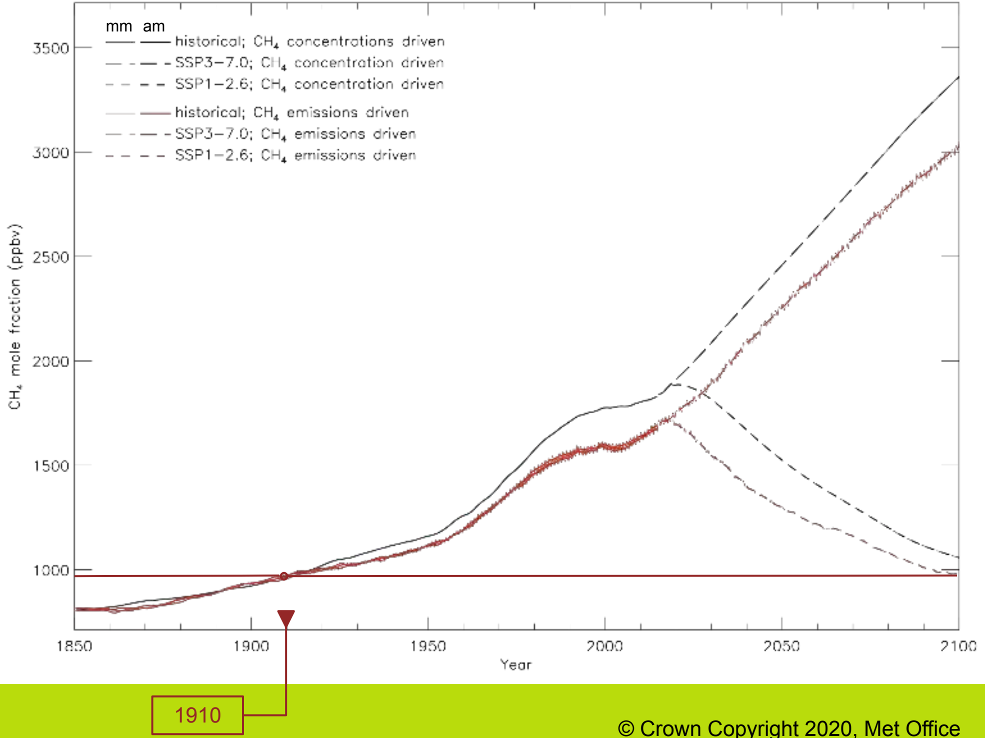
$Error_{\Delta(PI \rightarrow PD)}$ in 2014: approx. -200 ppbv
$\%Error_{\Delta(PI \rightarrow PD)}$ in 2014: approx. -20%

similar CH_4 auto-feedback in both configurations



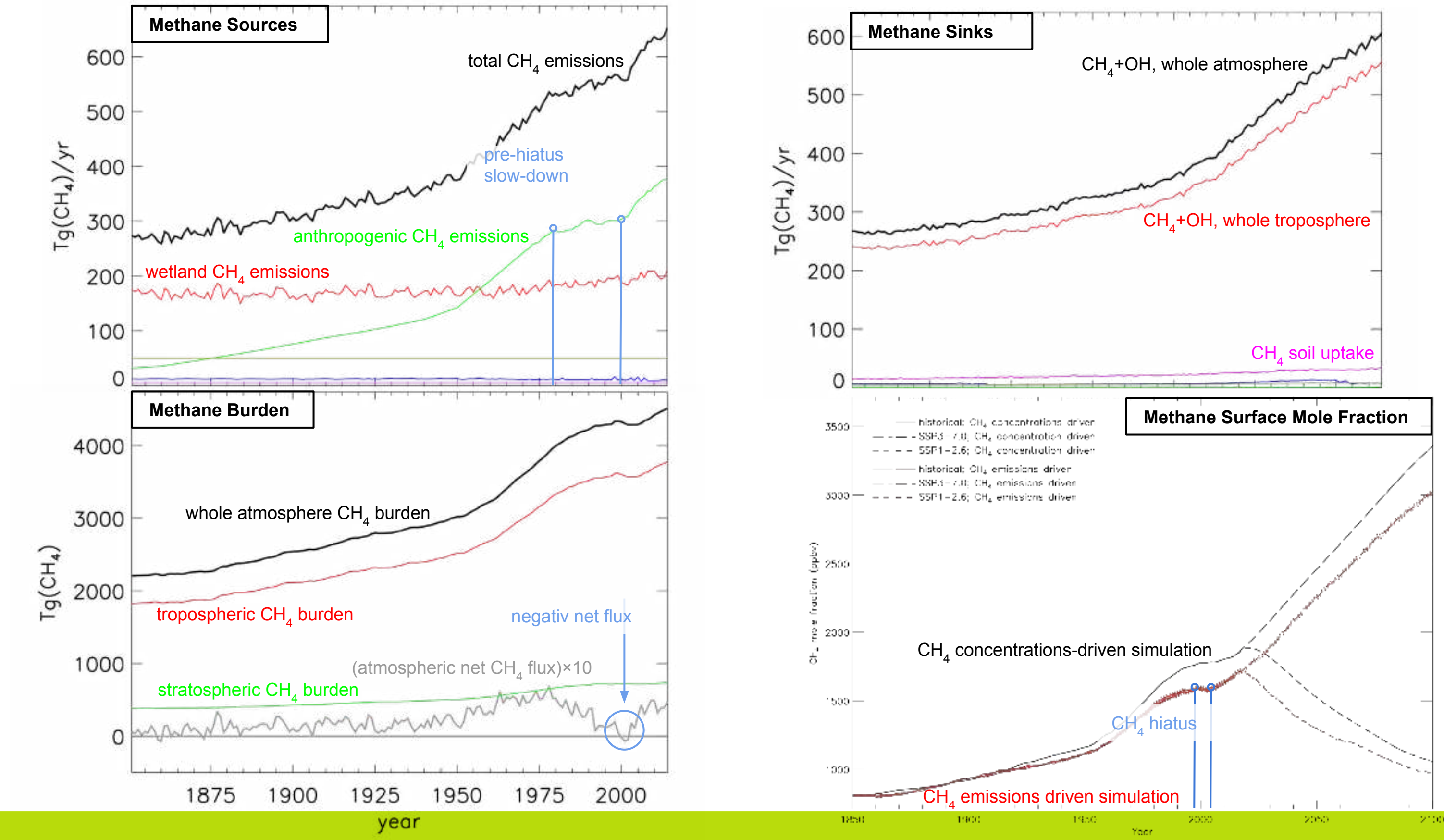
CH_4 Recovery under SSP1-2.6

	Atmospheric Methane Content	
	surface mole fraction	whole atmosphere burden
1910s	986 ppbv	2675 Tg
2090s*	992 ppbv (+1%)	2750 Tg (+3%)
	Main Methane Sources (Tg/yr)	
	wetlands	anthropogenic
1910s	169.3	91.6
2090s*	219.4 (+30%)	118.9 (+30%)
	Main Methane Sinks (Tg/yr)	
	CH_4+OH✦	Soil Uptake
1910	-287.7	-18.7
2090s*	-384.1 (+34%)	-20.7 (+11%)



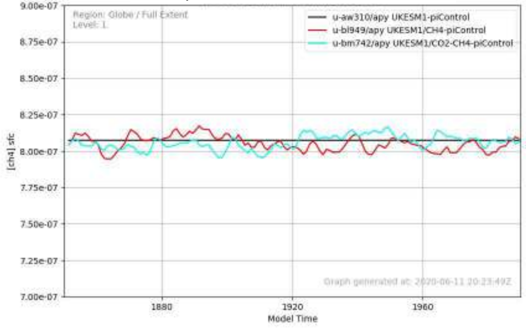
*for SSP1-2.6
✦whole atmosphere

Simulating The Hiatus

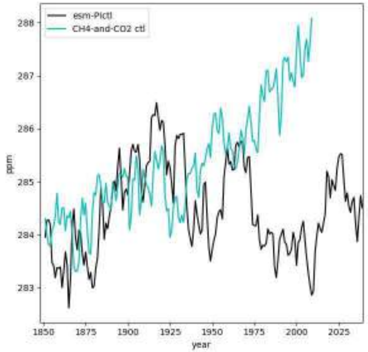


CO_2/CH_4 Emission-Driven UKESM1

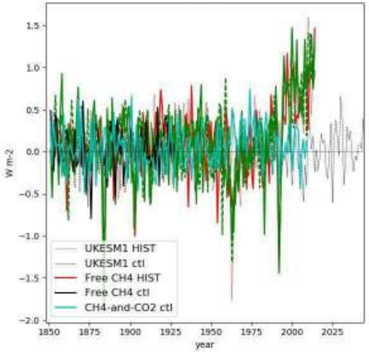
CH_4 Surface Mass Mixing Ratio

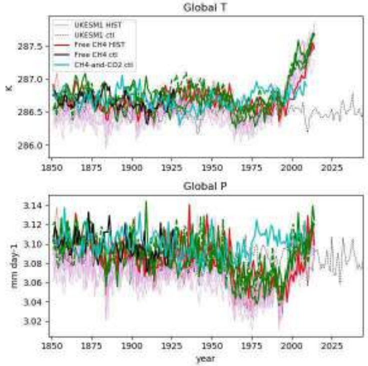


CO_2 Surface Concentrations

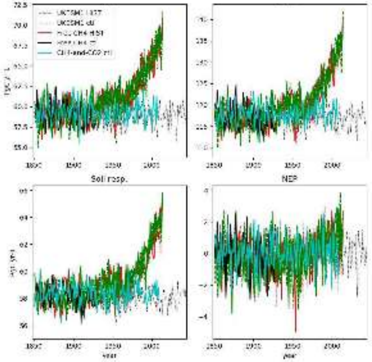


Net TOA Flux





Terrestrial Carbon Fluxes



- UKESM1.0 release configuration (CMIP6 piControl)
- UKESM1.0 CH_4 emission-driven configuration
- UKESM1.0 CO_2/CH_4 emissions-driven configuration

Adam Povey

NCEO, University of Oxford

Evaluation of aerosol in the UKESM against an ensemble of satellite observations

Adam Povey, NCEO @ Uni. Oxford

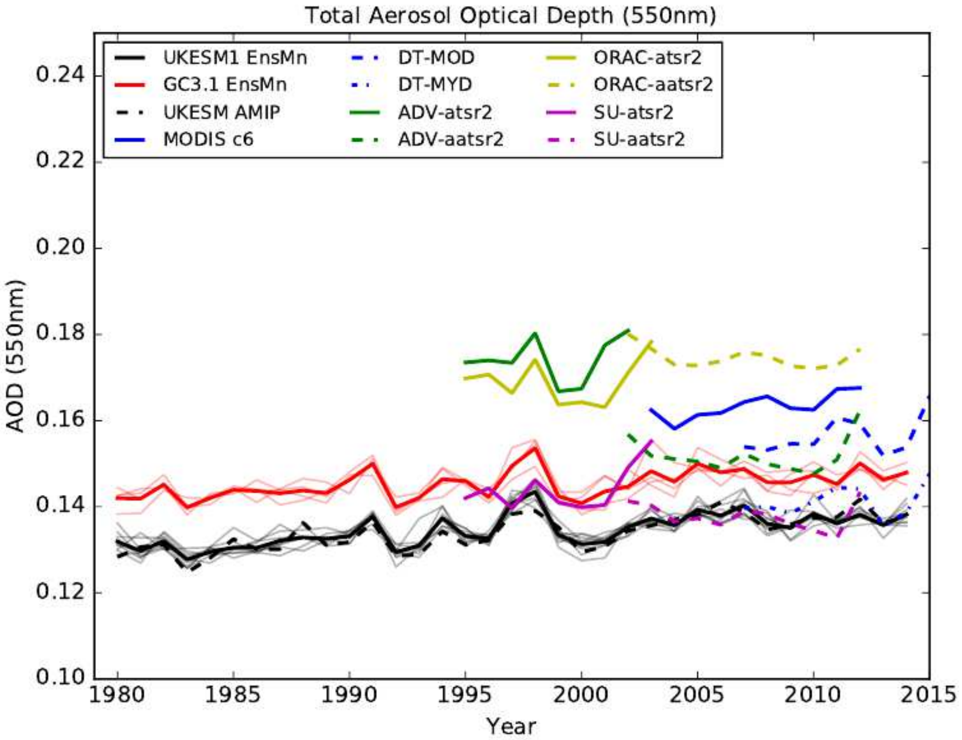


Image credit: Jane Mulcahy, Met Office (under review in Geosci. Model Devel.)

- Aerosol in models is traditionally evaluated by comparing monthly averages to those from MODIS or AERONET.
  - It's a simple comparison to perform but glosses over differences between the all-time average output by a model and the clear-sky, time-limited average from data.
- We can do a little better by comparing against a range of satellite observations.
  - Shown opposite are global, annual means from UKESM (black), GC3.1 (red), MODIS (blue), and three AATSR algorithms (green, purple, yellow).
  - While the magnitudes differ significantly, the tendency is quite similar. For example, all time series shown capture the El Nino in 1998.

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UKRI Natural Environment Research Council

Evaluation of aerosol in the UKESM against an ensemble of satellite observations

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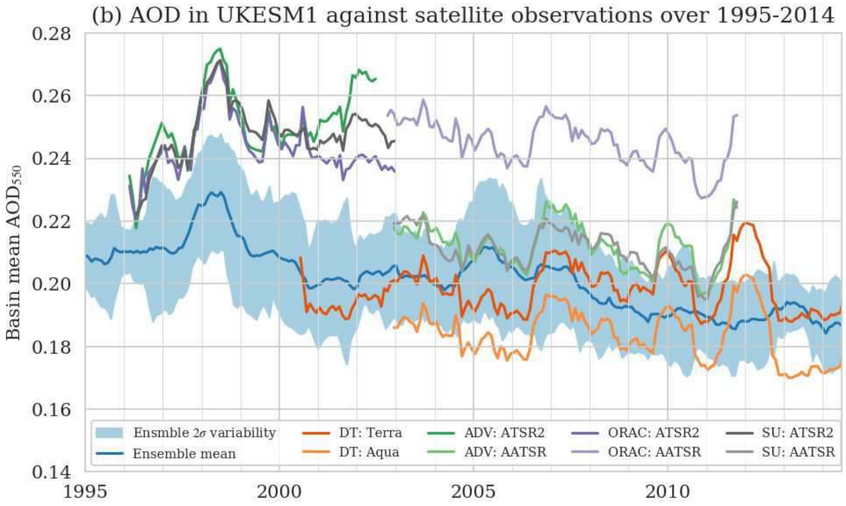
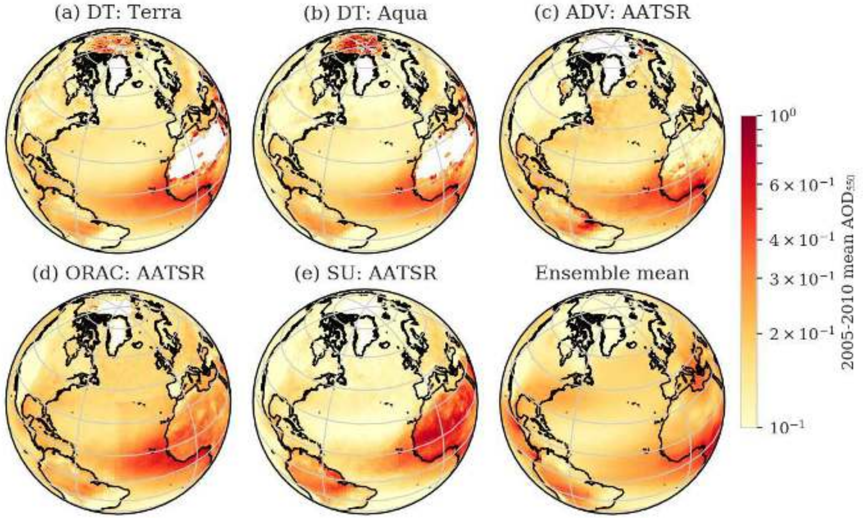


Image credit: Adam Povey (under review in J. Adv. Model. Ear. Sys.)

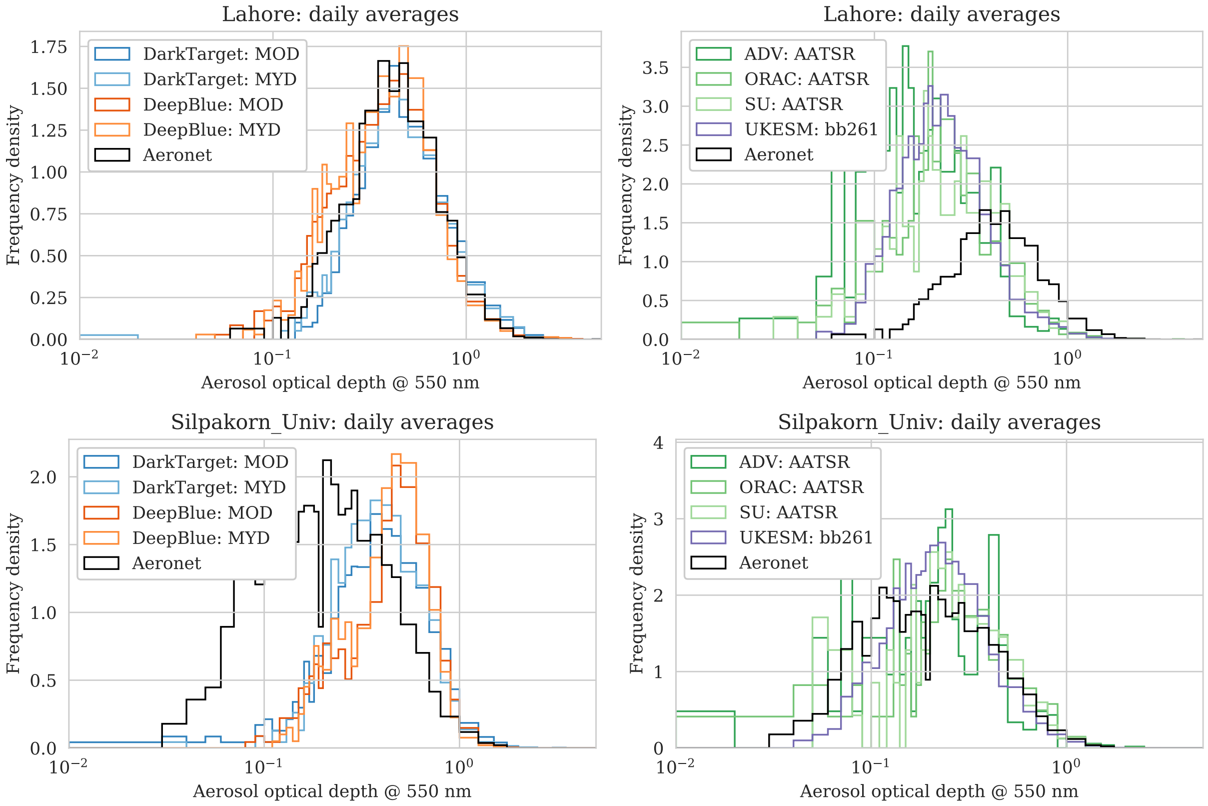


- We can do a little better still by focusing on a particular region and/or shorter time steps.
  - Here we highlight monthly mean AOD over the north Atlantic. The time series (left) average over the basin, showing that the model captures the decrease in AOD from 2008 but has missed something in 2012. The fields (right) average 2005-2010, showing disagreement over the difference in AOD between the mid and northern Atlantic.
  - The regional focus better isolates the cause of differences between datasets, such as the position of the Saharan outflow.

Evaluation of aerosol in the UKESM against an ensemble of satellite observations

Adam Povey, NCEO @ Uni. Oxford

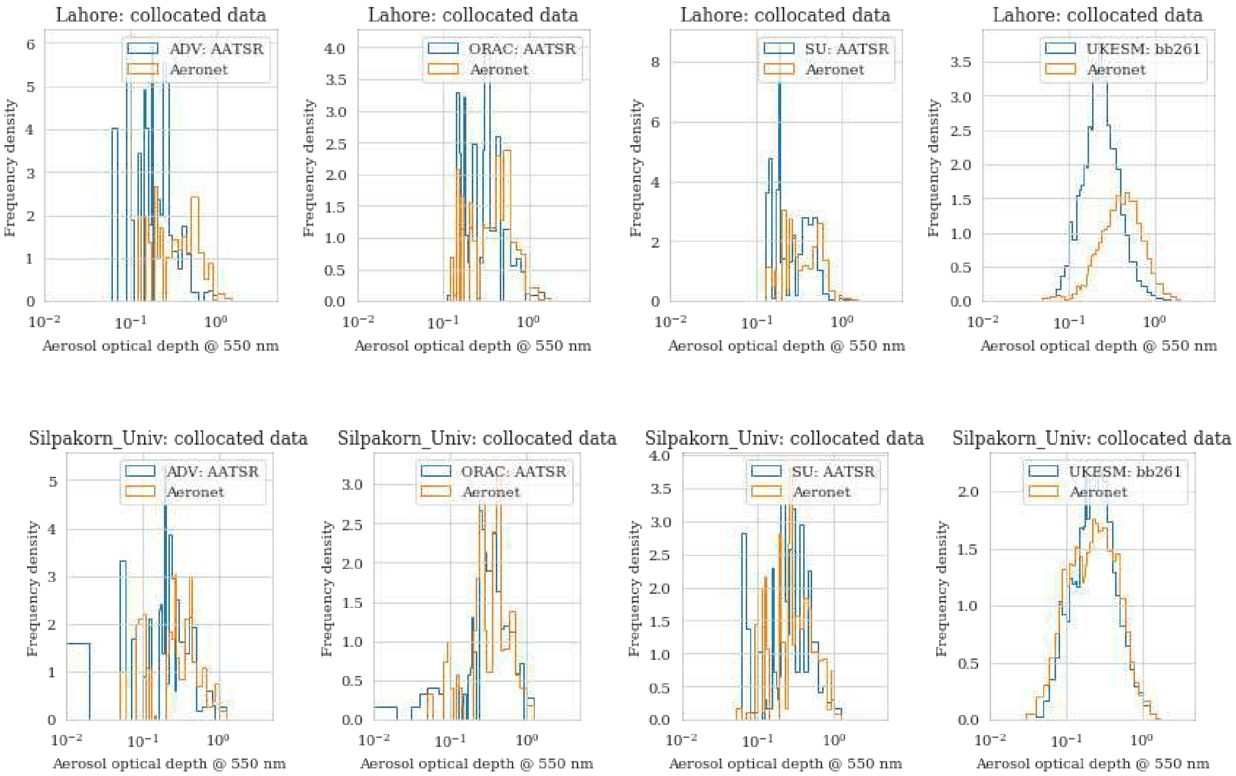
- Using the dedicated UKESM run with high temporal resolution output, we can look at the distribution of daily averages and concentrate on specific ground sites.
  - Shown opposite are the histograms of daily average AOD from AERONET (black), MODIS (left), AATSR, and the UKESM (right).



Evaluation of aerosol in the UKESM against an ensemble of satellite observations

Adam Povey, NCEO @ Uni. Oxford

- Using the dedicated UKESM run with high temporal resolution output, we can look at the distribution of daily averages and concentrate on specific ground sites.
- We can also precisely collocate the model with observations, showing that it agrees with AERONET about as well and any of the satellites do.



Paul Griffiths

NCAS

Tropospheric ozone burden and budgets in AerChemMIP experiments

Paul Griffiths, James Keeble, Lee Murray, Guang Zeng, Matthew Shin, Oliver Wild, Paul Young, Alex Archibald, Fiona O'Connor, Sungbo Shim, Jane Mulcahy, N. Luke Abraham, Mohit Dalvi

and Ben Johnson, Gerd Folberth, Catherine Hardacre, Olaf Morgenstern, Joao Teixeira, Steven Turnock, Jonny Williams
(UKCA AerChemMIP team)

and Vaishali Naik, Louisa K. Emmons, Ian Galbally, Birgit Hassler, Larry W. Horowitz, Jane Liu, David Tarasick, Simone Tilmes, and Prodromos Zanis
(CMIP6 paper co-authors)

https://doi.org/10.5194/acp-2019-1216

National Centre for Atmospheric Science
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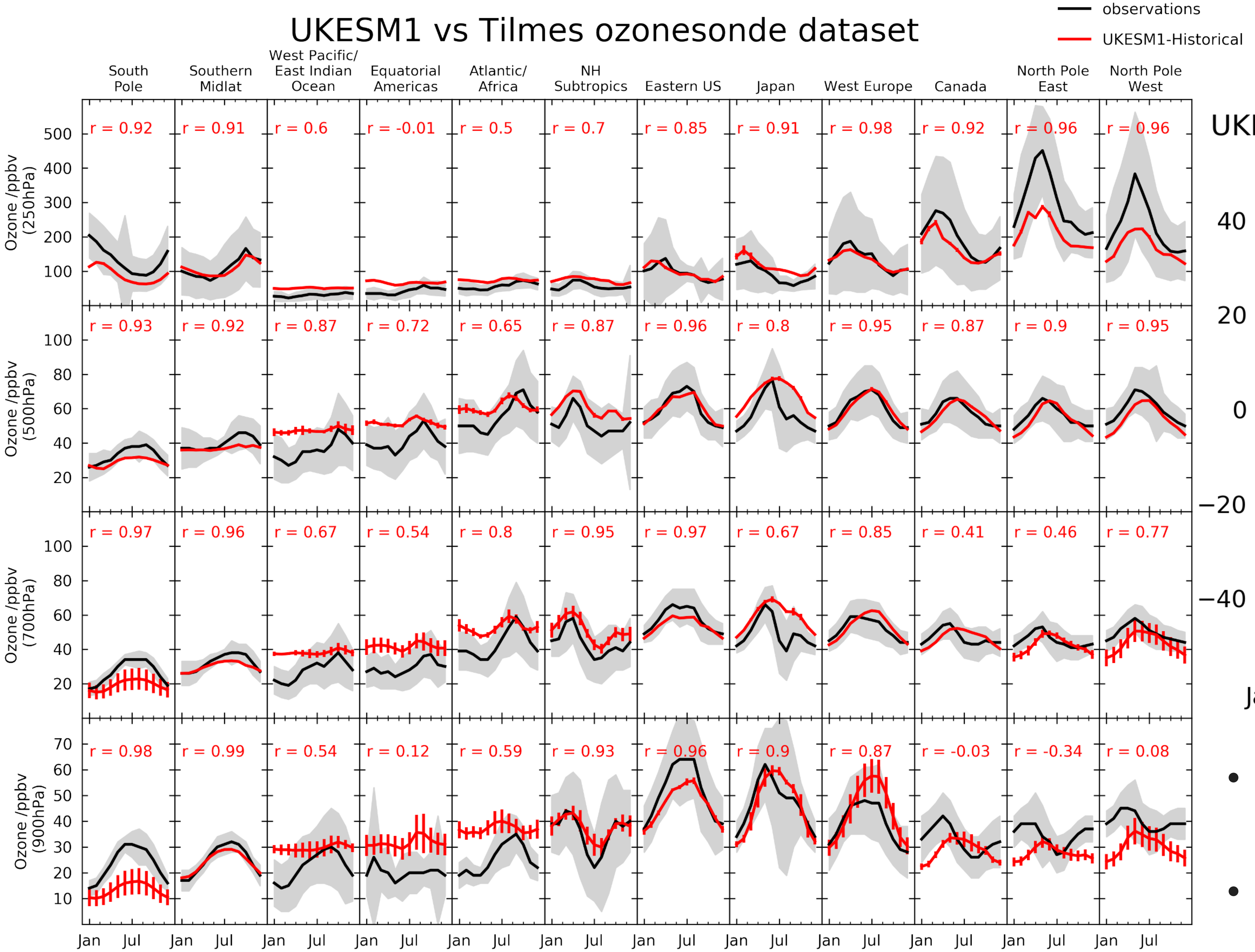
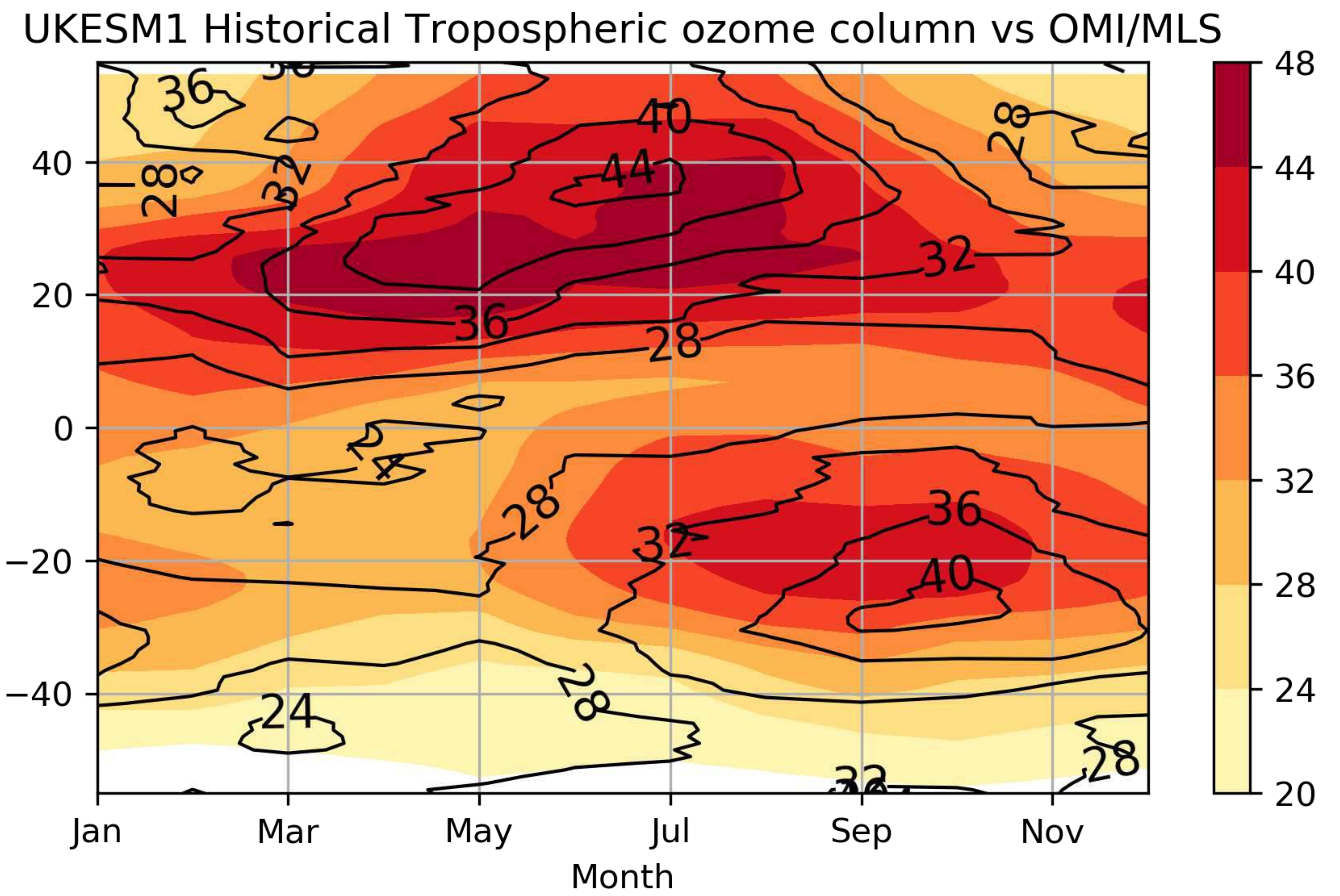
How does UKESM1 tropospheric ozone compare against observations?

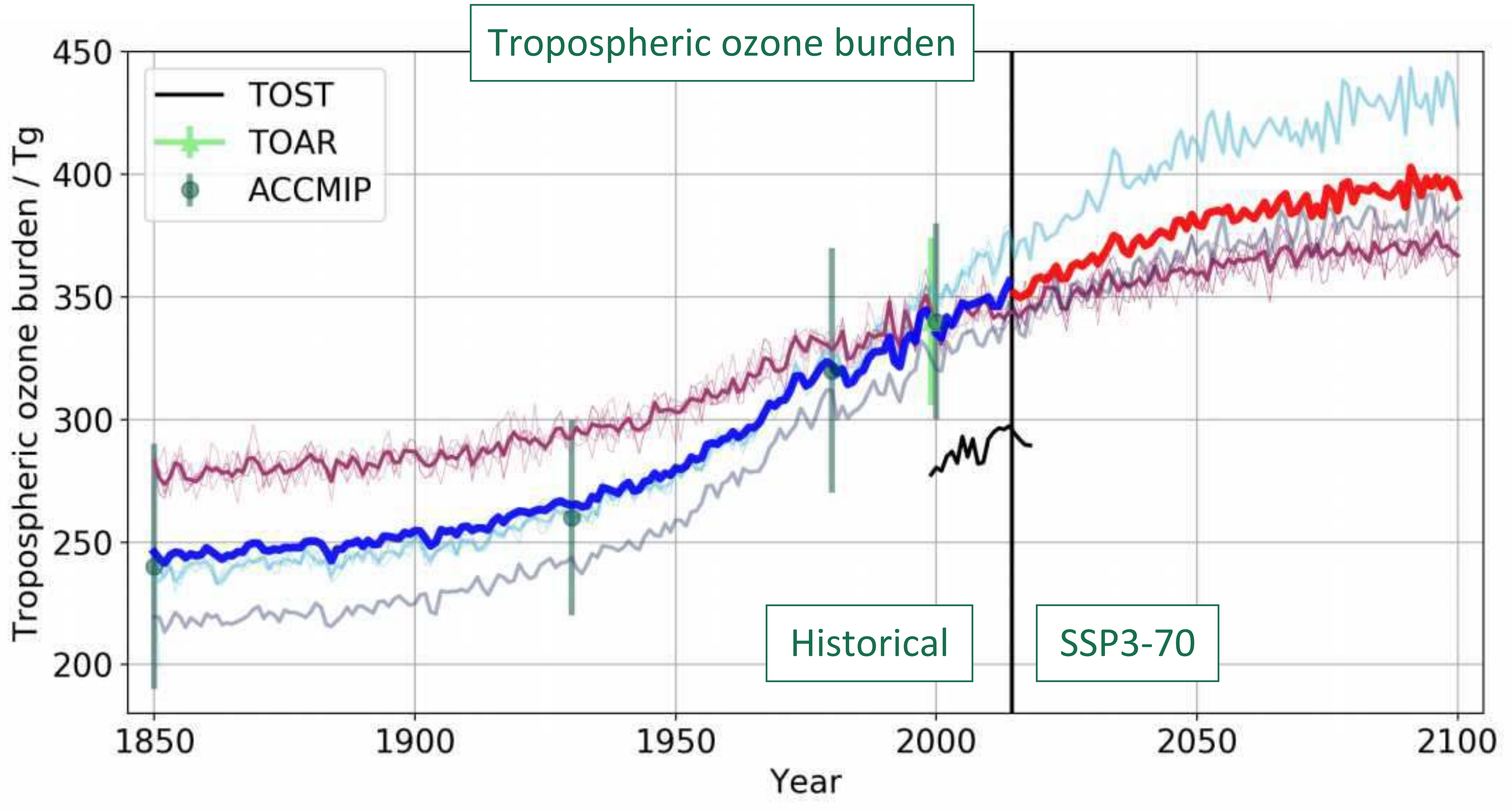


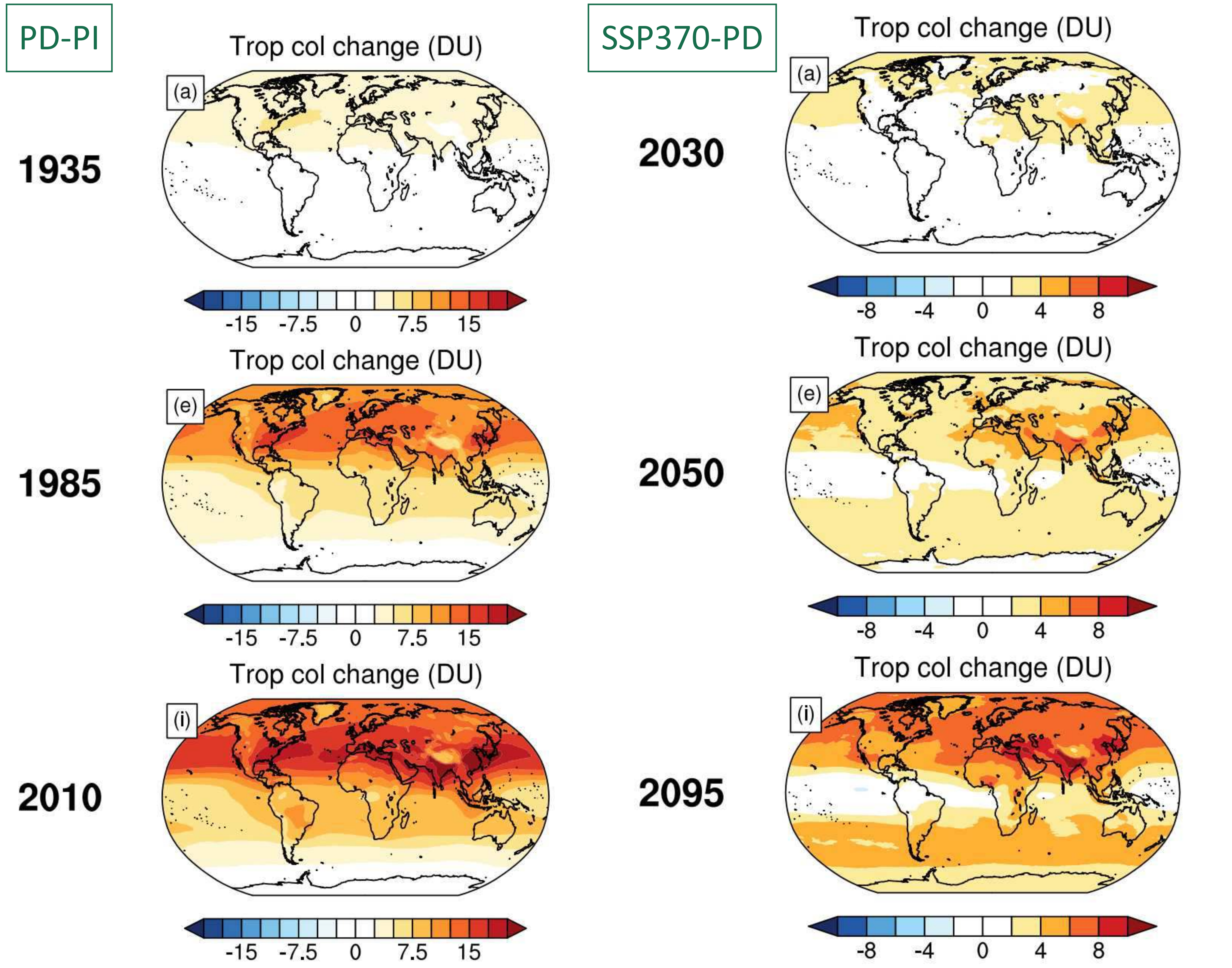


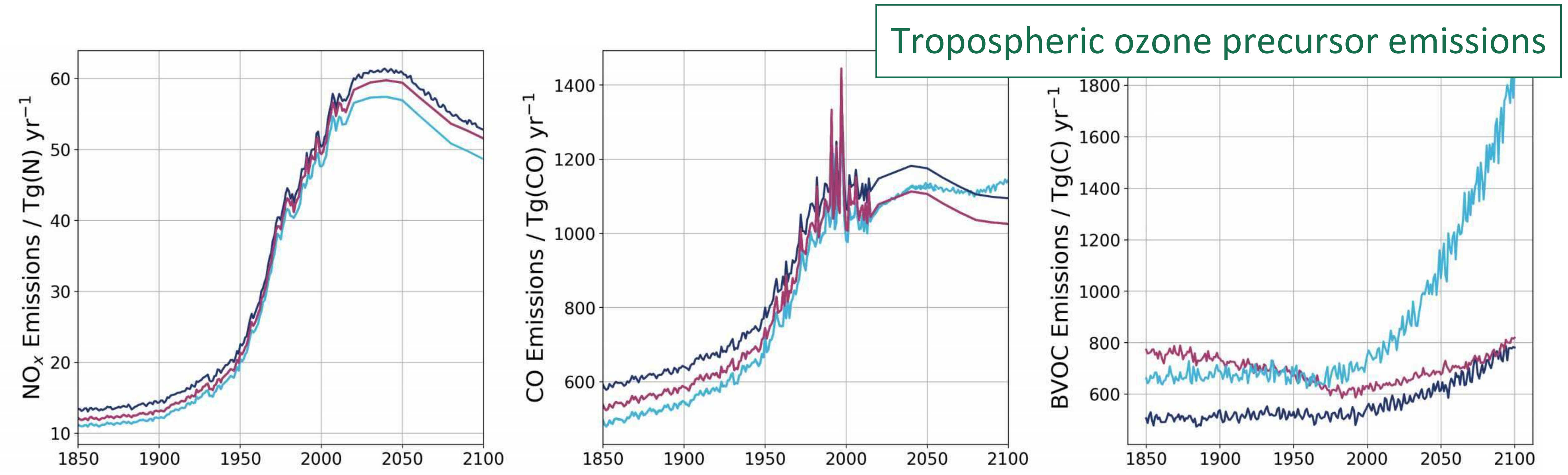
- UKCA tropospheric ozone compares well with observations, particularly in-situ .
- Integrated quantities, such as column amounts, sensitive to tropopause definition.

How does tropospheric ozone burden evolve in CMIP6?

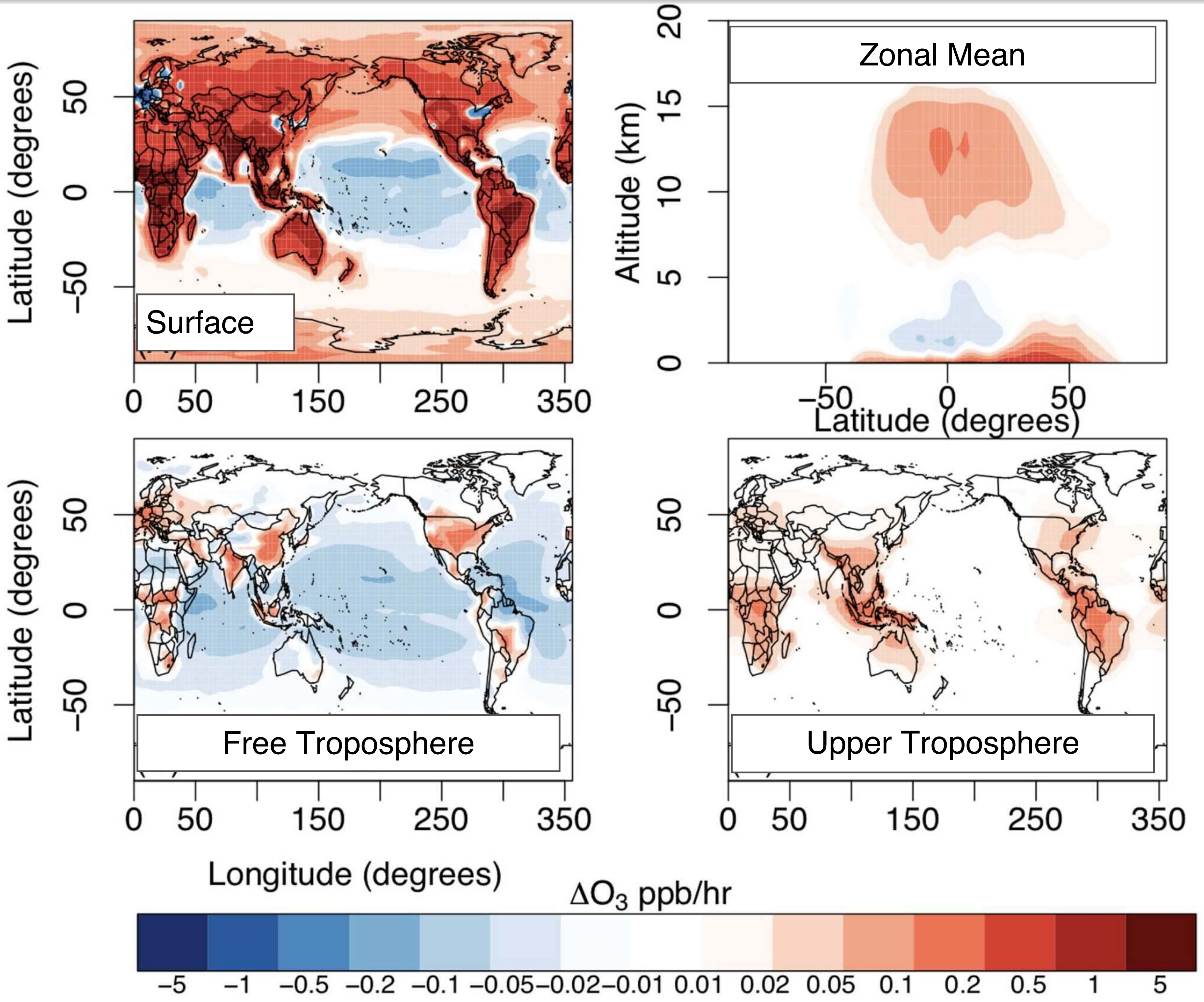
- Analysis so far has focused on CMIP Historical and ScenarioMIP SSP3-70 experiments, for which suitable diagnostic output was available.
- Picture has changed little since CMIP5, MM range is also similar.
- Ozone burden increased by about 40% from 1850 levels of 240 Tg (MMM) with steepest rate of increase around 1960.
- In SSP3-70, the rate of growth of the burden declines further, as NOx emissions start to fall along this pathway after 2050.
- Nevertheless, strong local changes in ozone seen regionally at the end of the century.

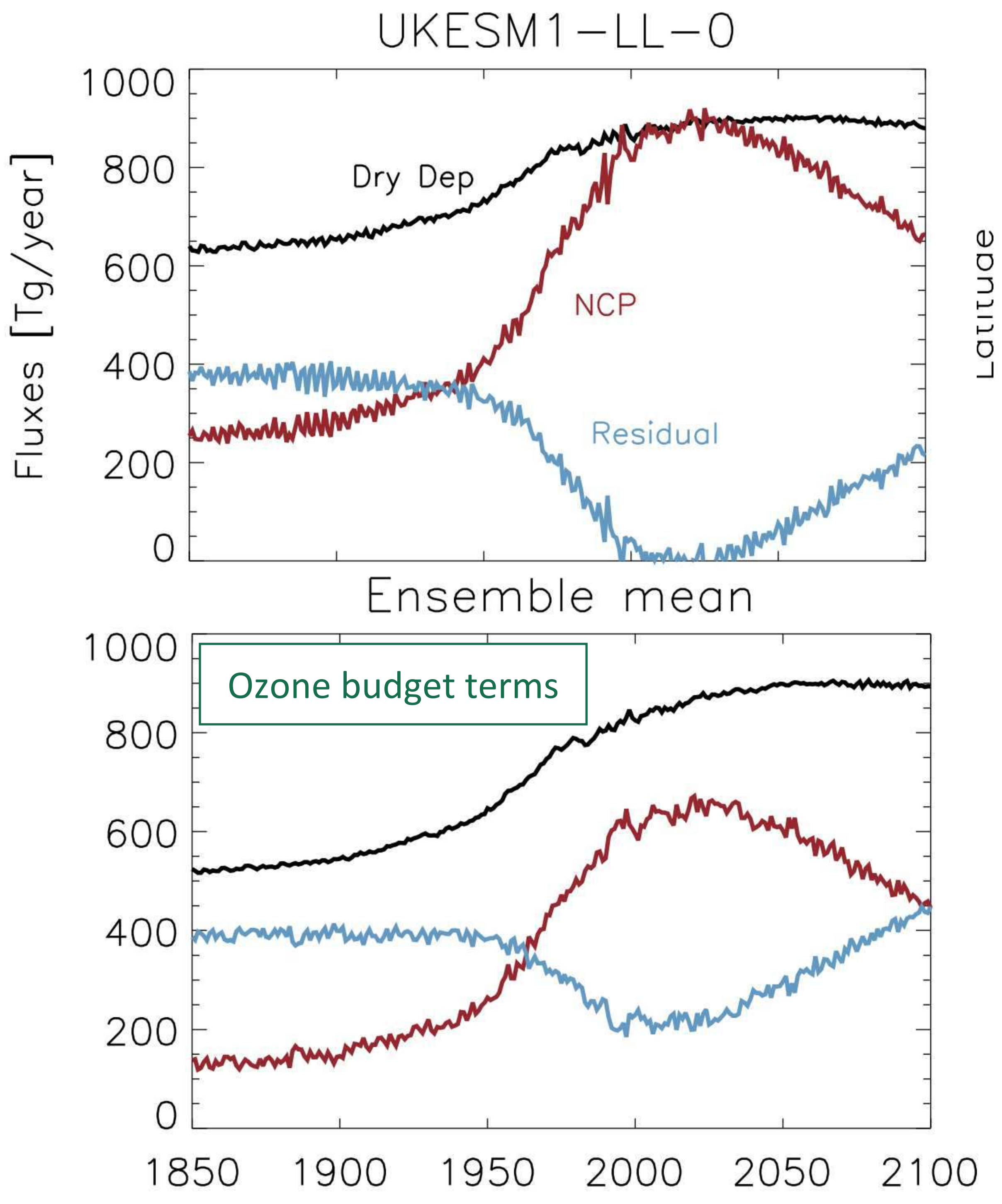


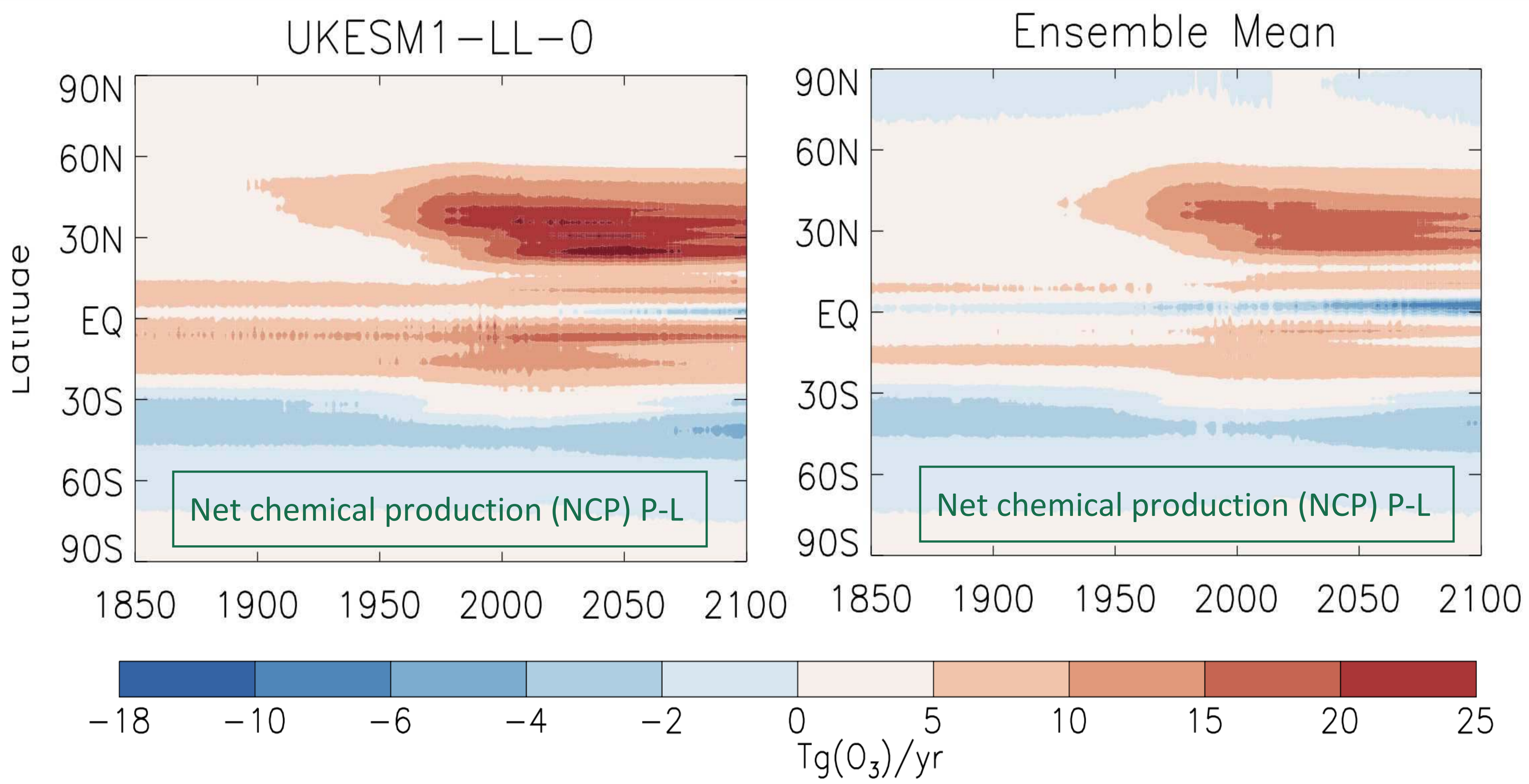


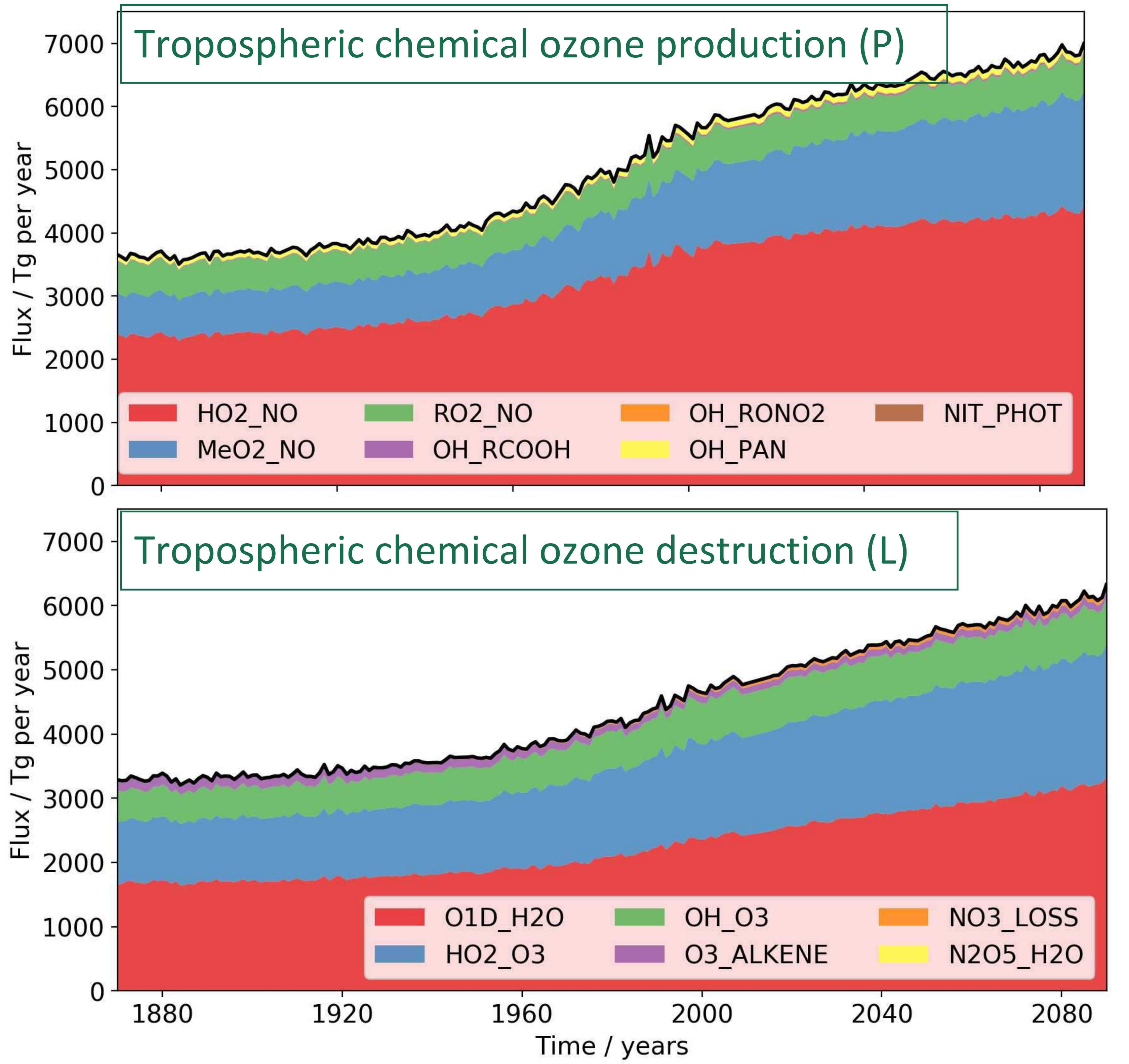


How does tropospheric ozone budget evolve in CMIP6?





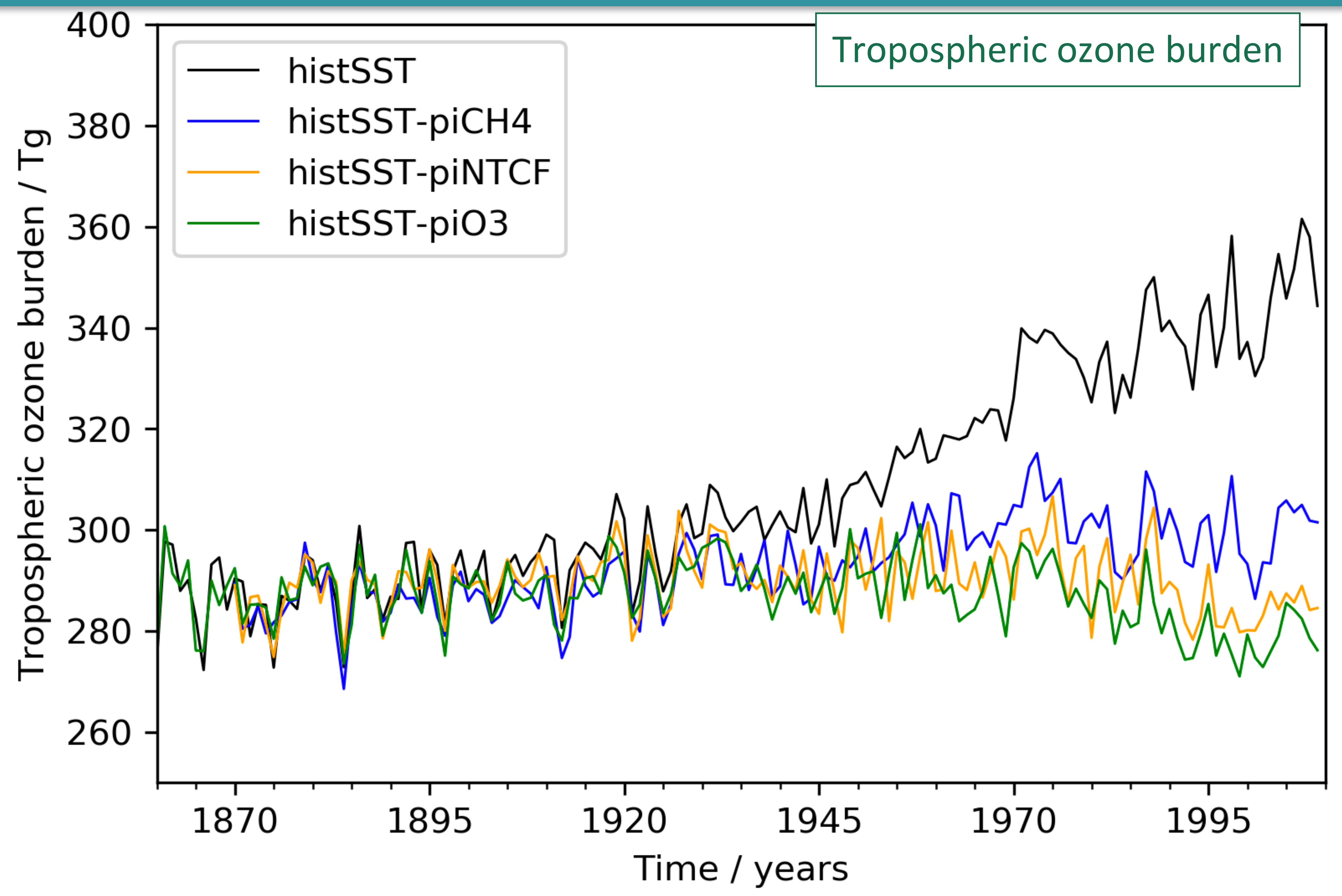




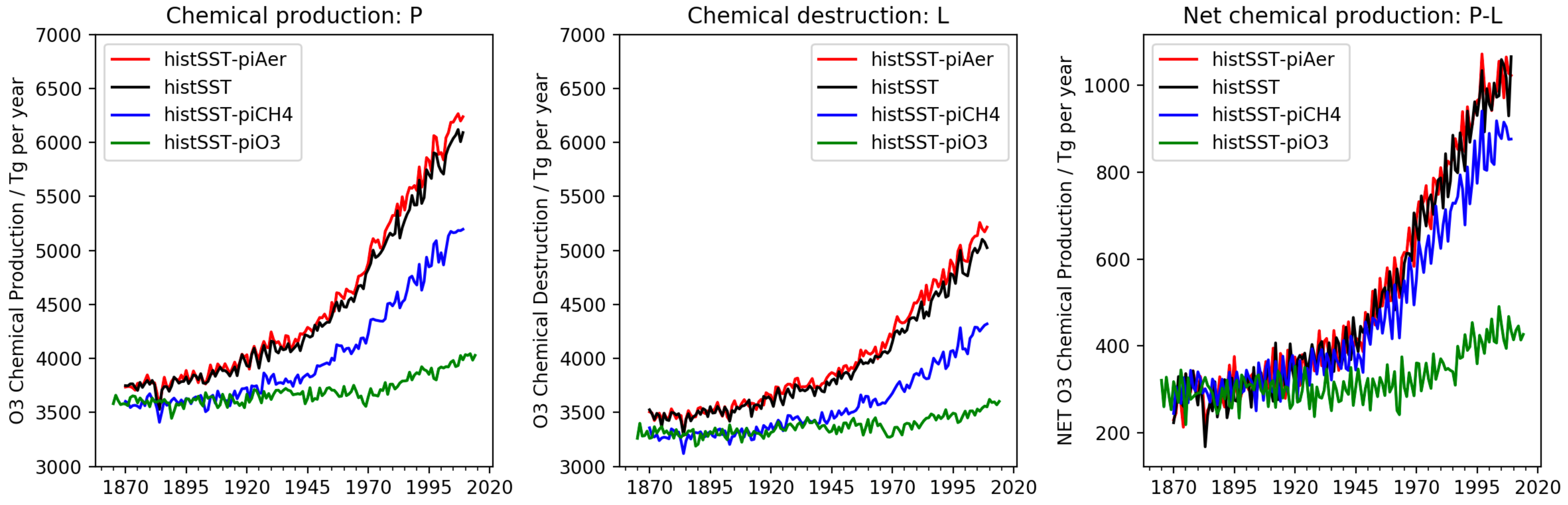
- Ozone burden is controlled by balance between chemical production and loss, transport from the stratosphere and deposition at the surface. Production and loss occur in different regions.
- Significant changes in all these terms, CMIP6 diagnostics limit analysis somewhat
  - Increased emissions of VOCs, including BVOCs, contribution of methane increasing.
  - More NOx, including LNOx.
  - Location of emissions in NH shifting southwards at end of 20th century
- Different drivers for O_3 production over the 21st century with an important contribution from CH_4.

What does AerChemMIP add to CMIP6?

- AerChemMIP is a CMIP6 sub-project aimed at isolating effect of chemically active gases and aerosol on climate via tiered attribution experiments.
    - Selected components held at 1850 levels, other forcings evolve along historical trajectories.
    - Using atmosphere-only configuration with SSTs from historical experiments
- Initial results – 10% change in ozone burden when CH_4 held at PI levels, with larger changes to individual terms in chemical ozone budgets; 20% change when ozone precursors held at 1850 levels. P-L only part of the story.



Experiment_ID	CH4	N2O	Aerosol Precursors	Ozone precursors	CFC/HCFC	Tier
histSST	Hist	Hist	Hist	Hist	Hist	1
histSST-piNTCF	Hist	Hist	1850	1850	Hist	1
histSST-piAer	Hist	Hist	1850	Hist	Hist	2
histSST-piO3	Hist	Hist	Hist	1850	Hist	2
histSST-piCH4	1850	Hist	Hist	Hist	Hist	1
histSST-1950HC	Hist	Hist	Hist	Hist	1950	1
histSST-piN2O	Hist	1850	Hist	Hist	Hist	2



Graham Mann

University of Leeds

“UKESM volcano-climate experiments: Comparing impacts from satellite-based (CMIP6-GloSSAC) and microphysically-consistent (SMURPHS-UKCA) Pinatubo volcanic forcing datasets”

Graham Mann[1,2], Wuhu Feng[1,2], Sandip Dhomse[1,3], Alex Rap[1], Martyn Chipperfield[1,3], Nicolas Bellouin[4], Beatriz Monge-Sanz[5,6], Lesley Gray[5,6], Ben Johnson[7] and Jim Haywood[7,8]

1: School of Earth and Environment, University of Leeds
2: National Centre for Atmospheric Science, University of Leeds
3: National Centre for Earth Observation, University of Leeds
4: Department of Meteorology, University of Reading
5: Department of Physics, University of Oxford
6: National Centre for Atmospheric Science, University of Oxford
7: Earth System and Mitigation Science, UK Met Office
8: College of Engineering, Mathematics and Physical Sciences, Univ. Exeter

UKESM | ACSIS | National Centre for Atmospheric Science NATURAL ENVIRONMENT RESEARCH COUNCIL | UKCA

http://ukesm.ac.uk | https://www.ncas.ac.uk/en/acsis-home http://www.ukca.ac.uk
http://acsis.ac.uk/articles/item/17-placing-volcanic-eruptions-in-north-atlantic-climate-simulations

Co-ordinated multi-model experiments to quantify short-term and long-term climate response to the radiative forcings from volcanic aerosol clouds from major tropical eruptions.

"Initial conditions ensemble" climate model experiments apply the same volcanic forcing in a protocol to enact volcanic forcing across different modes of climate variability within CMIP6 control integrations.

Short-term response explored in "volc-pinatubo experiment" -- idealized climate model experiments off CMIP6 pre-industrial control integration – clean volcano-climate response experiment (no other forcings)

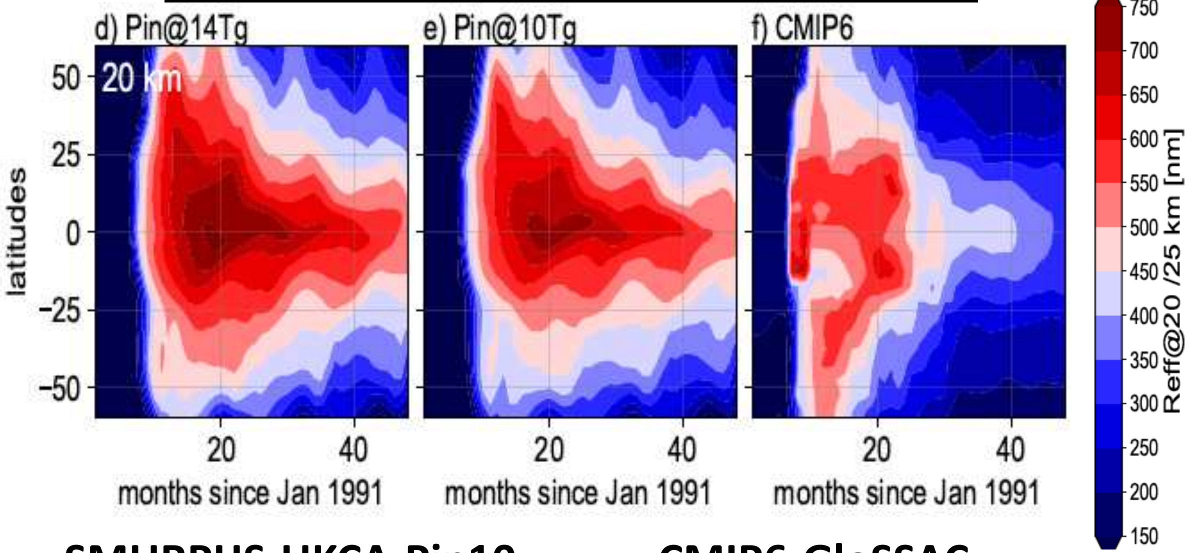
-- **models apply the CMIP6-GloSSAC forcing dataset for Pinatubo**, applying this same volcanic forcing in 27-member ensemble: 3 members in each of warm/neutral/cold ENSO and +ve/neutral/-ve NAO to explore variation in short-term response e.g. re: winter-warming effect (Robock and Mao, 1992)

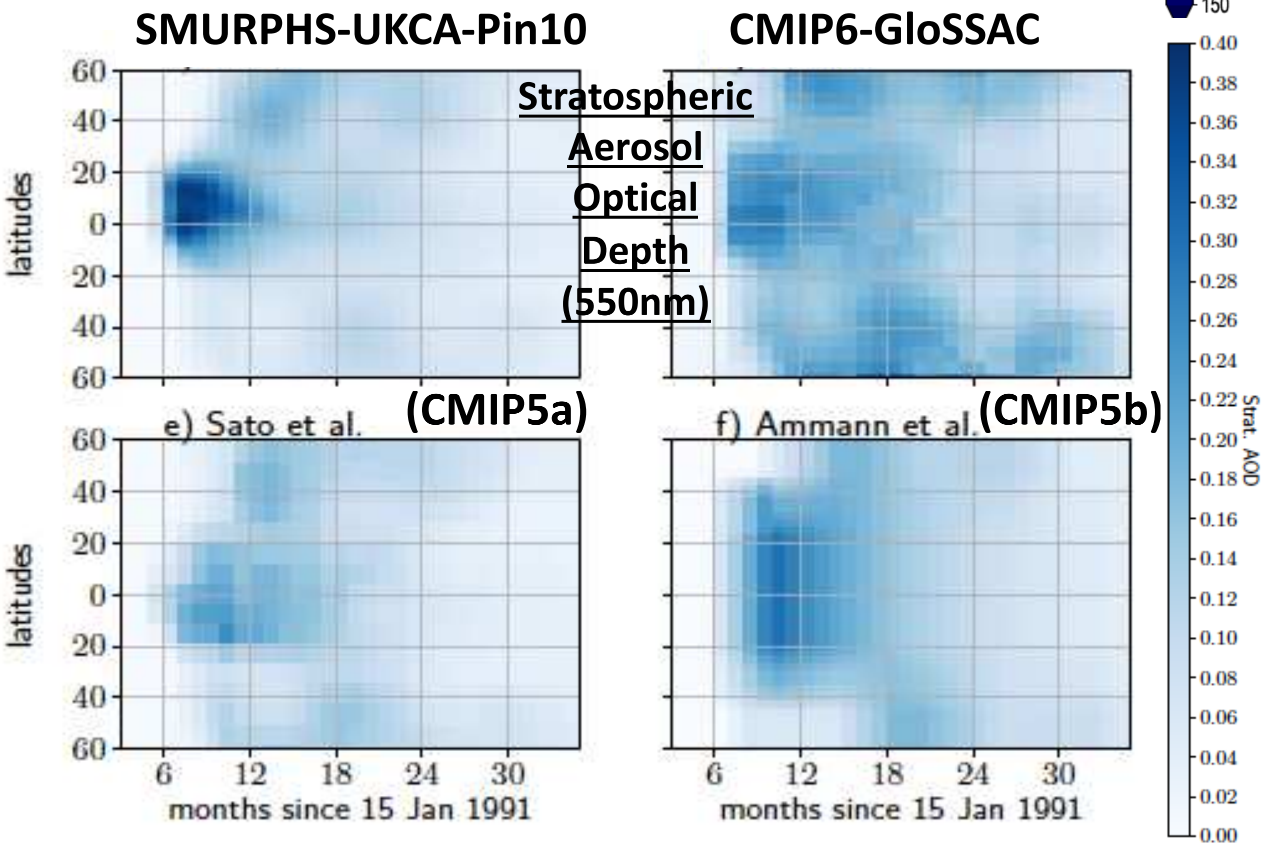
One part of NCAS contribution to NERC long-term science programme on the North Atlantic climate (ACSIS) is to assess the influences of major volcanic eruptions on climate and stratospheric composition.

NCAS researchers at Leeds (Wuhu Feng, Graham Mann) have run the UKESM volc-pinatubo experiment and have generated a new "microphysically-consistent" Pinatubo aerosol dataset from GA4 UM-UKCA interactive stratospheric aerosol simulations for the NERC highlight topic on the hiatus (SMURPHS)

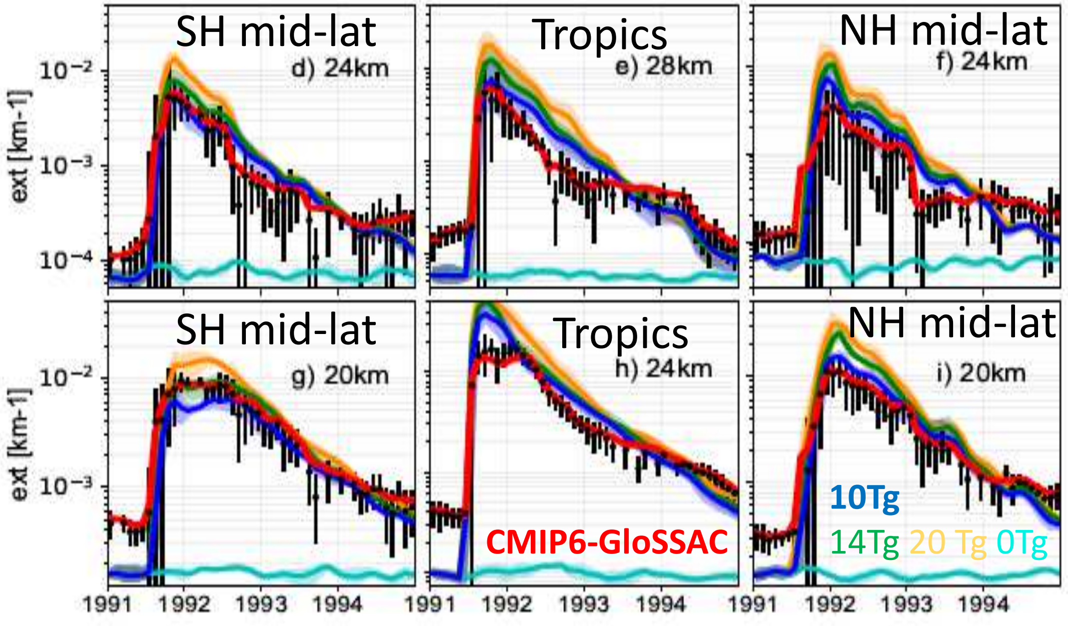
For ACSIS, running 2nd UKESM volc-pinatubo ensemble with SMURPHS microphysically-consistent forcing.

Volcanic aerosol particle size (effective radius)





Volcanic aerosol extinction in stratosphere (at 550nm)



Dhomse et al. (2020, in review, ACP Discussions)

https://doi.org/10.5194/acp-2020-344
Preprint. Discussion started: 6 May 2020

Atmospheric Chemistry and Physics Discussions
Open Access

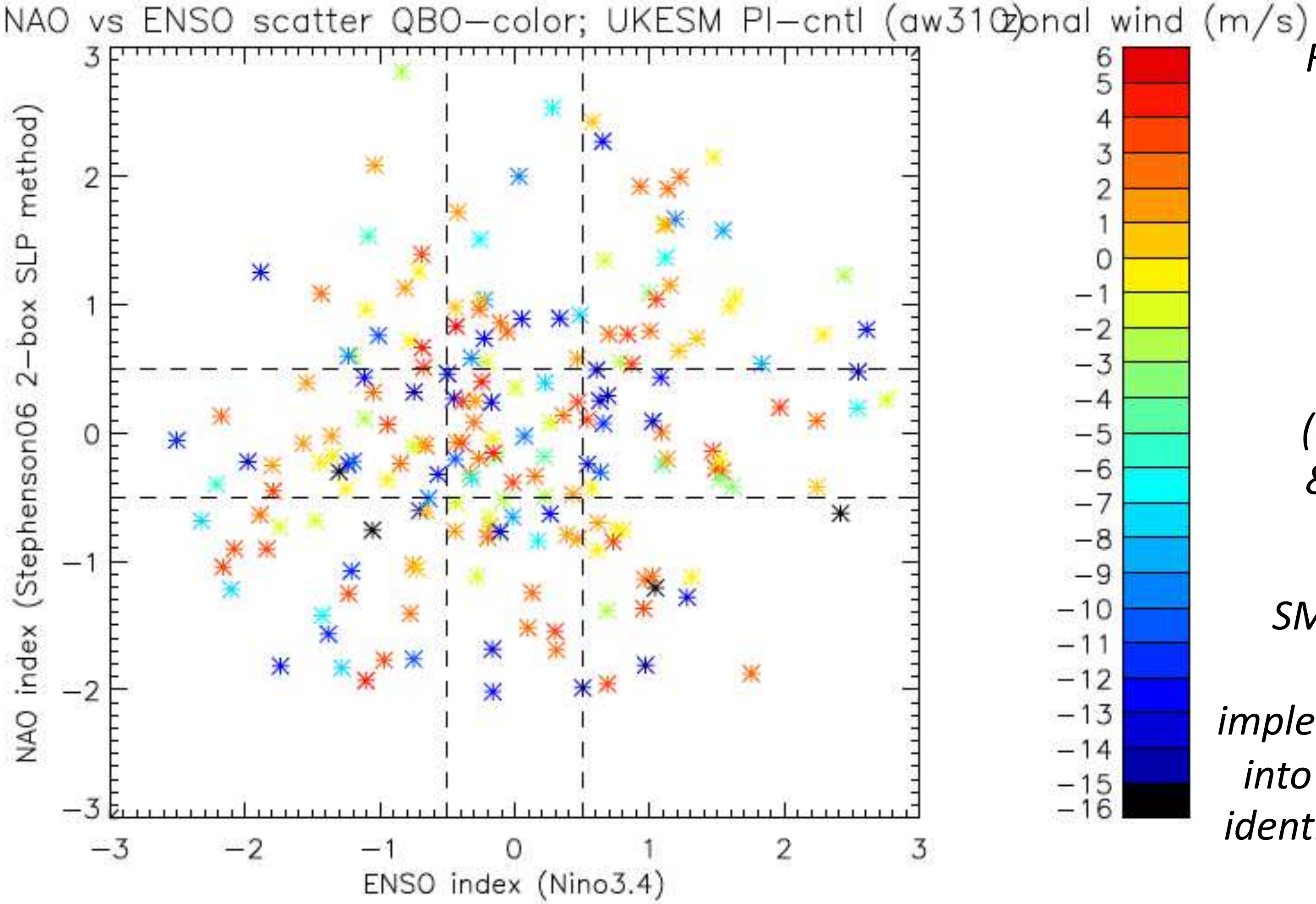
Evaluating the simulated radiative forcings, aerosol properties and stratospheric warmings from the 1963 Agung, 1982 El Chichón and 1991 Mt Pinatubo volcanic aerosol clouds

Sandip S. Dhomse[1,2], Graham W. Mann[1,3], Juan Carlos Antuña Marrero[4], Sarah E. Shallcross[1], Martyn P. Chipperfield[1,2], Ken S. Carslaw[1], Lauren Marshall[1,5], Nathan Luke Abraham[5,6], and Colin E. Johnson[3,7]

[1]School of Earth and Environment, University of Leeds, Leeds, UK
[2]National Centre for Earth Observation, University of Leeds, Leeds, UK
[3]National Centre for Atmospheric Science (NCAS-Climate), University of Leeds, UK
[4]Department of Theoretical Physics, Atomic and Optics, University of Valladolid, Valladolid, Spain
[5]Department of Chemistry, University of Cambridge, Cambridge
[6]National Centre for Atmospheric Science, University of Cambridge, UK
[7]Met Office Hadley Centre, Exeter, UK

Correspondence: Sandip Dhomse (s.s.dhomse@leeds.ac.uk), Graham Mann (g.w.mann@leeds.ac.uk)

Initial conditions analysis of UKESM PI-control for volc-pinatubo experiments
(each years' seasonal *ENSO and NAO indices for DJF* and *"QBO-index" for July-Dec*)



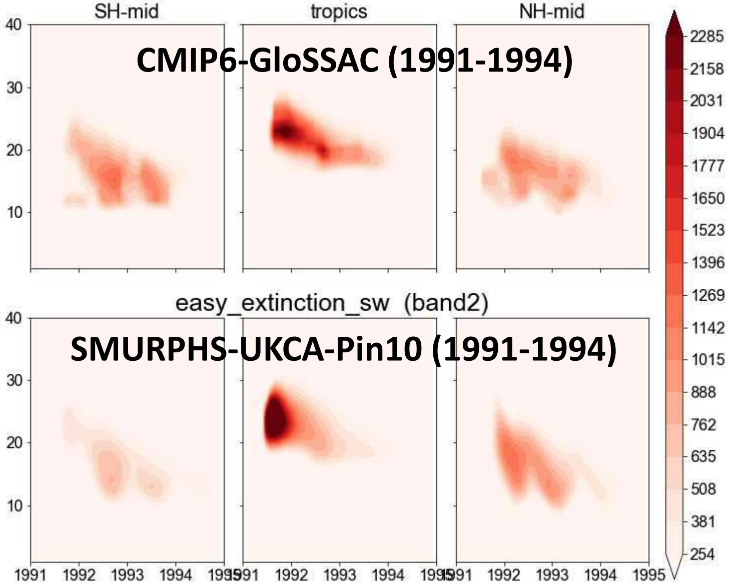
offline RADAER used to convert UKCA aerosol to easy aerosol (ext, abs & asym)

SMURPHS dataset implemented into UKESM identically to CMIP6

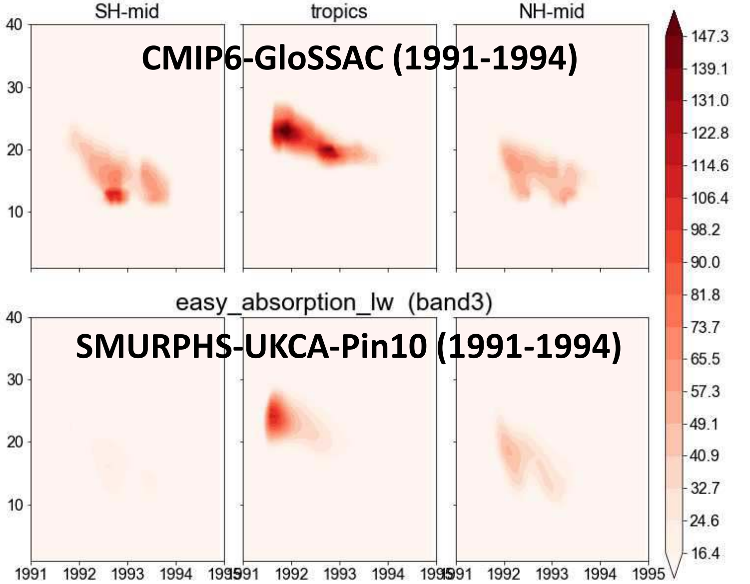
Wuhu Feng (NCAS, Leeds) ran 27-member UKESM ensemble from easterly-QBO (blue)
Potential to analyse westerly-QBO ensemble & contrast vortex & climate response.

We encourage members of the UKESM community to work with us to evaluate the broad range of simulated responses effected in the UKESM VolMIP runs.

extinction in SW band 2 (320nm to 690nm)
(i.e. solar dimming in mid-visible)



absorption in LW band 3 (12.5μm to 18.2μm)



Lee de Mora

PML

PML | Plymouth Marine Laboratory

Listen to the ocean

Earth System Music: the creation and reach of music generated from UKESM1

Lee de Mora, A. Sellar , A. Yool , J. Palmieri , R.S. Smith, T. Kuhlbrodt, R. J. Parker, J. Walton , J. C. Blackford , C.G. Jones

UKESM

@LeedeMora https://www.youtube.com/c/LeedeMora

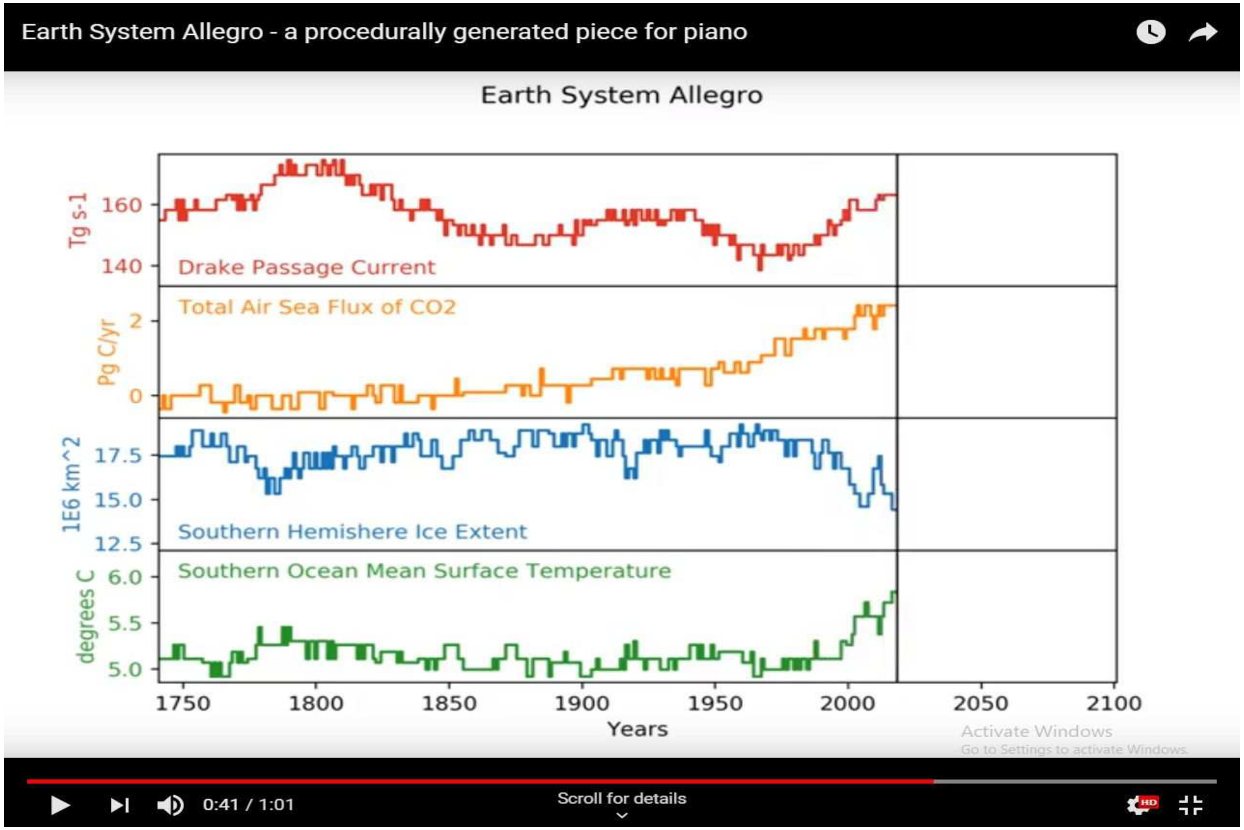
Earth System Music - pilot study

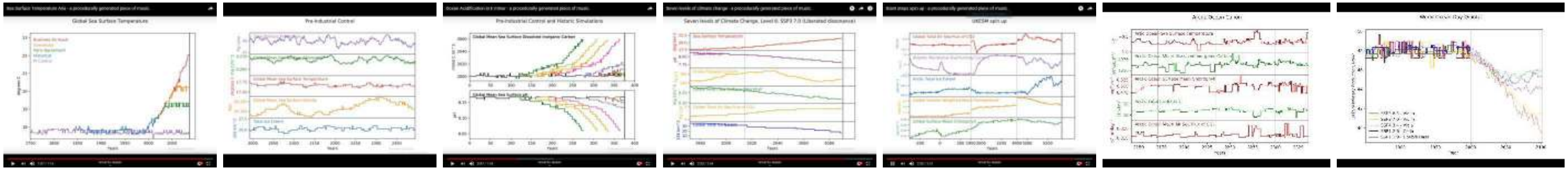
Sonification: The use of non-speech audio to convey information.

UKESM1 ocean time series data used to generate eight musical pieces and videos.

Diverse behaviors of modelling, scientific and musical contexts:

- UKESM Spin up, Pre-industrial control, Historical, future scenarios
- Circulation, Marine carbon cycle, sea ice extent Sea surface temperature, Ocean Acidification, primary production.
- Allegro, Vivaci, “4 chord song”, *12-bar blues*, Minor aria, Lizzo’s *juice*, Pachelbel’s *Canon,* string quintet





@LeedeMora https://www.youtube.com/c/LeedeMora

Methodology

Model Data and Pre-processing

UKESM1
Model data in NetCDF format

BGC-val
Python based model evaluation toolkit

Time series shelves
BGC-val processed output data

UKESM

BGC-val

Legend

File
Box with thick border

Process
Arrow with no border

Earth System Music Processor

Earth system music processor settings
Python dictionary containing all required settings, artistic choices and paths to data.

Load settings
Includes data selection criteria and artistic choices.

Load shelve data
Access UKESM1 data as time series

Apply smoothing window
Removes some of the temporal variability

Convert data to MIDI pitch
Uses data range provided

Enforce scale or chord
Uses artistic choice

Set MIDI velocities
Adjust note loudness

Remove duplicate notes

Extend final note

Process MIDI and model data into images

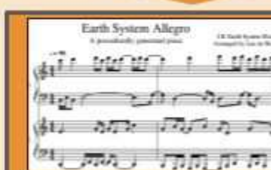
Output notes as MIDI

Post Processing

Video frame images
png format

Musical Instrument Digital Interface (MIDI) file

Musescore
Loads MIDI as sheet music.



Sheet music
pdf format

Timidity++ Piano player
Piano synthesizer

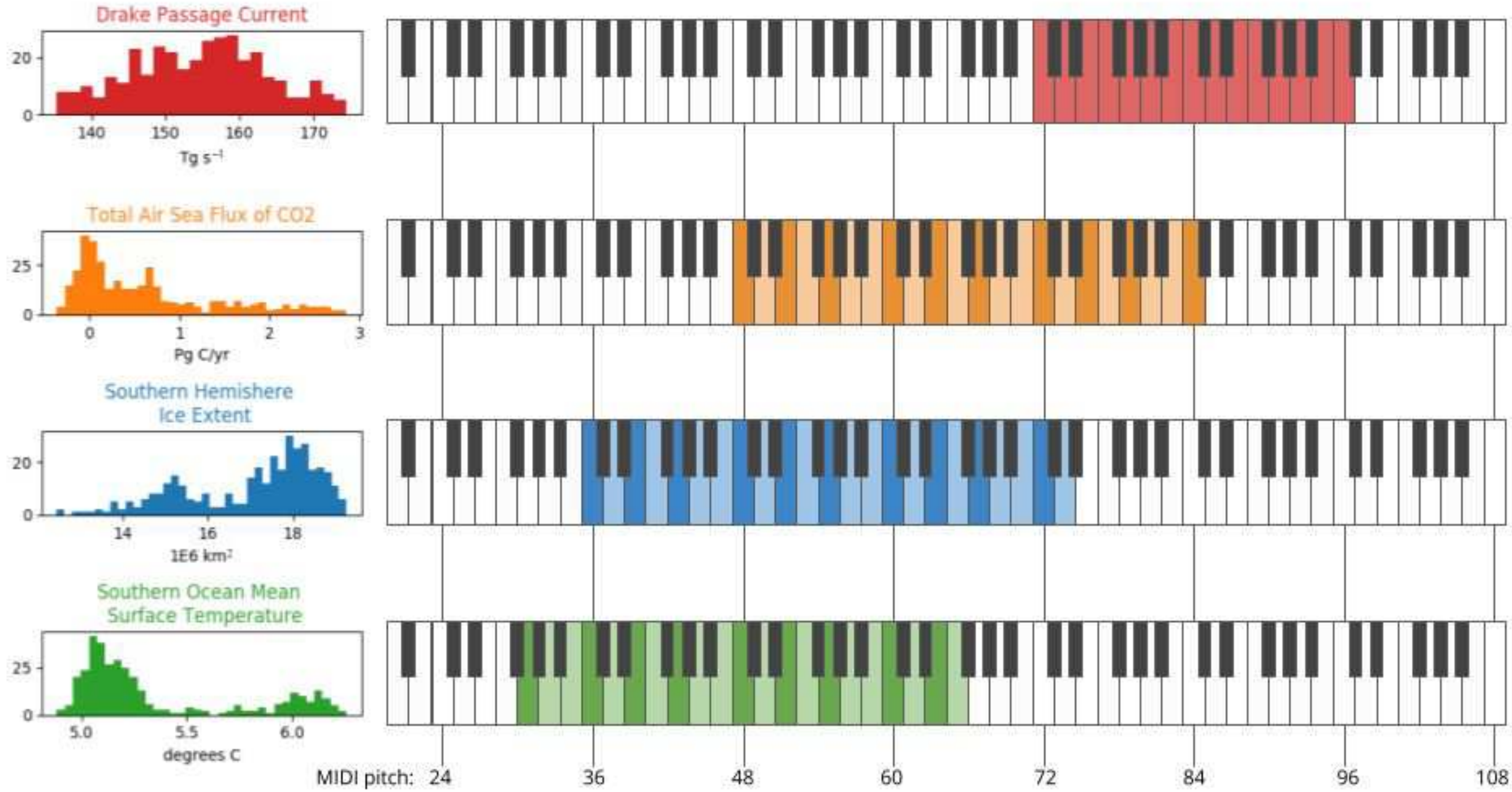
MP3 audio
Performance by piano synth

Ffmpeg video processor
Combines images and audio to produce video

Final Video
Audio and video in mpeg format

PML | Plymouth Marine Laboratory

Musical range and artistic decisions



- The choice of datasets used to determine pitch and velocity
- The pitch and velocity ranges
- Width of the smoothing window
- Tempo & the number of notes per beat
- Key and chord progressions
- The choice of instruments
- Title
- Style
- Mastering

These choices allow the composer to attempt to define the emotional context of the piece. ie:

SSP1 1.9: optimistic & free

SSP5 8.5: uneasy & foreboding

Quantifying the reach

Videos posted on YouTube, shared via author's personal & professional social media networks, or shown at conferences (NCEO, UKESM, EGU, UK-CMIP6)

View count & demographics tracked using YouTube Studio.

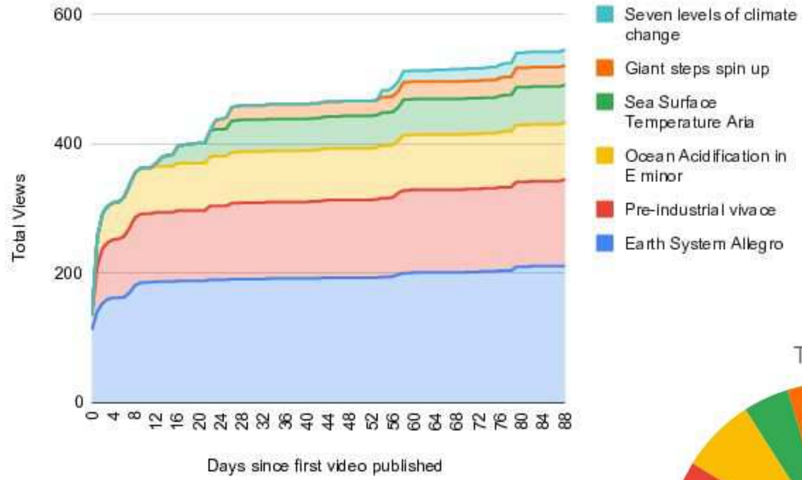
Audience comments also recorded.

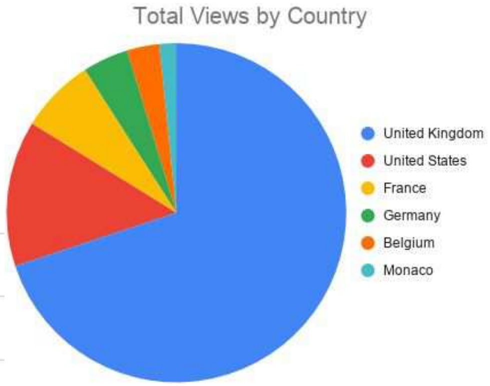
First 90 days: 525 views, 247 unique viewers, 465 minutes watch time.

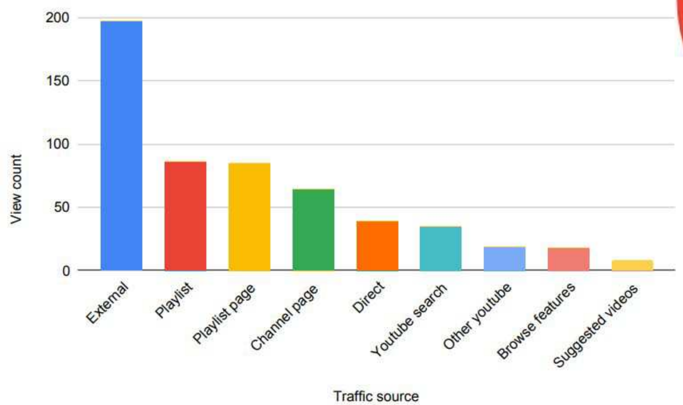
Overall:

2.3K views, 35 hours watch time, many positive comments.

Possible Extensions: Live performance; additional instruments, musical styles, models, domains; ESMValTool instead of BGC-val; include obserservations, create a viewer survey; additional in-video descriptions.







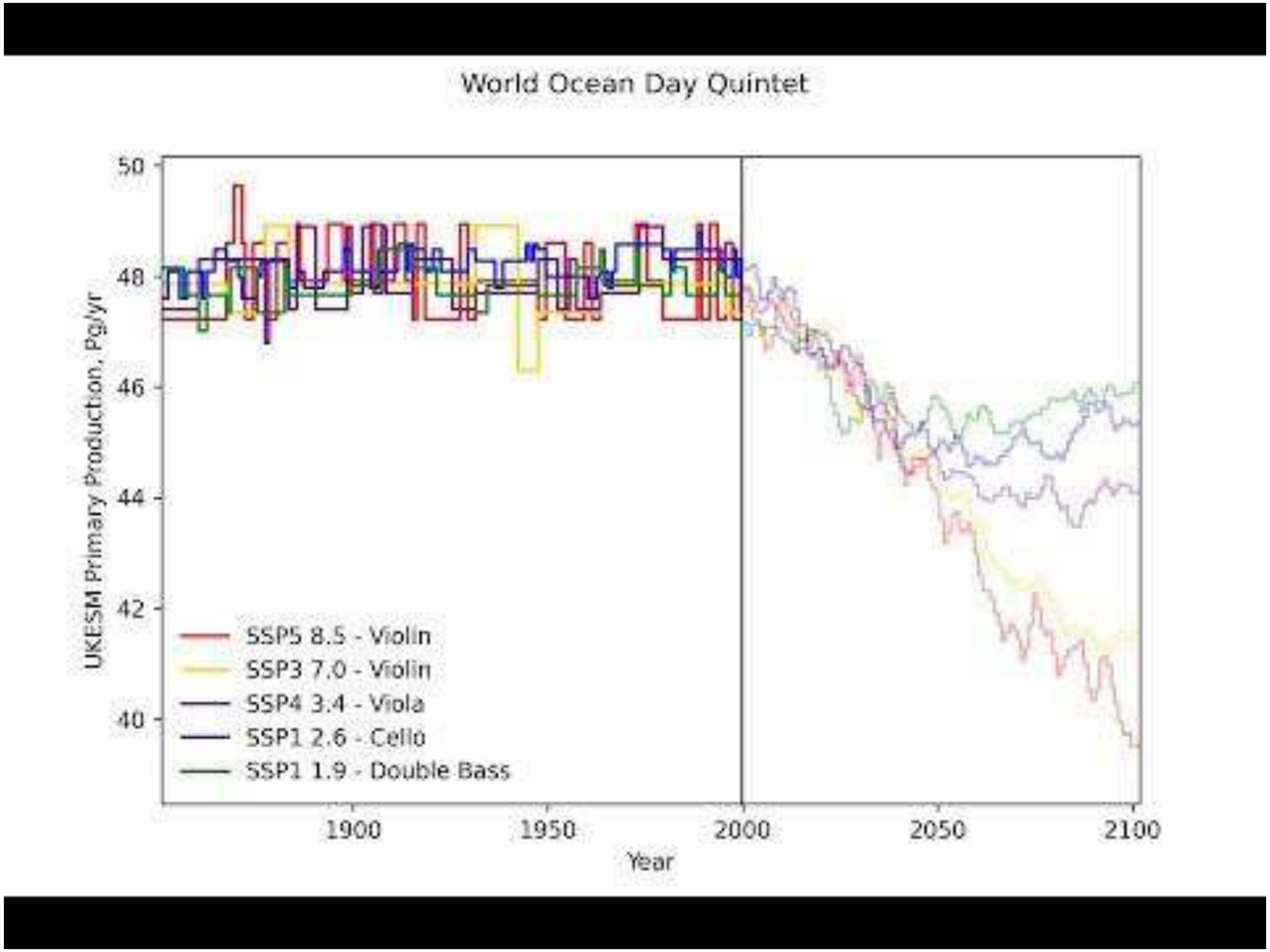
More details in Geoscientific Communications manuscript **GC-2019-28**: https://www.geosci-commun-discuss.net/gc-2019-28

@LeedeMora https://www.youtube.com/c/LeedeMora

Extra slide - latest video

New musical toolkit developed during lockdown, with many improvements:

- Faster and more transparent processing methods.
- Updated visual style.
- Higher frame rate & smoother video.
- Improved MIDI generation.
- Higher quality performance sampling.
- Studio effects (reverb, compression etc…)
- Improved audio mastering.
- Wide range of virtual instruments available.



[Earth System Music Playlist]()